

Chemical and Biological Sensor Standards Study



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Chemical and Biological Sensor Standards Study II

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Executive Summary

The current evaluation of chemical and biological sensors does not meet the needs of the operational community. Shortcomings include not only the determination of sensor performance metrics, but also the establishment of sensor requirements based on these metrics. In an effort to better accommodate the requirements of the operational community, the Defense Advanced Research Projects Agency initiated and the Defense Threat Reduction Agency completed a study designed to investigate the necessary chemical and biological sensor metrics and measurement protocols required to suitably design the next generation of chemical and biological sensor systems. Phase I of this study focused on developing a list of key metrics and the means to properly test sensors against those metrics. In the Phase I report, four straightforward scenarios were used that, while limited in scope, served as the basis for analysis and discussion.

This is the second phase of the study, and the scope and validity of the determination of sensor requirements has been expanded by utilizing 14 multirealization chemical and biological defense scenarios (Table I). In contrast to a single realization scenario (as was used in the Phase I Study), a multirealization scenario employs a range of agent release characteristics including, for example, total mass of agent, wind speed, geographic location, and other relevant parameters, and thus should provide a better set of sensor requirements than a single realization analysis.

	Scenario	Agent	Release Type	Release Comments
1	Convoy Movement	Anthrax	Single Point	Stationary sprayer
2	Convoy Movement	Sarin	Single Point	Stationary sprayer
3	Ground Forces Defense	Anthrax	Single Point	Stationary sprayer
4	Military Building (internal attack)	Smallpox	Single Point	Slow release from box
5	Military Building (external attack)	TIC	Single Point	Tanker truck release
6	Amphibious Operation	Mustard	Multiple Point	Mines
7	OCNUS Forward Airbase	VX	Multiple Point	Missile air bursts
8	Terrain Denial	VX	Multiple Point	Artillery air bursts
9	CONUS Military Post	Anthrax	Multiple Point	Backpack sprayers
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13	Naval Port Facility	Anthrax	Line	Moving truck with sprayer
14	Navy Ship in Littoral	Plague	Line	Small boat with sprayer

OCNUS – Outside Continental United States

CONUS – Continental United States

TIC – Toxic Industrial Chemical

VX and Sarin – Common names for two toxic chemicals

Table I. CB Defense Scenarios

Spider charts are a well recognized graphical method for displaying multidimensional data in a single plot. They are most useful when it is important to easily convey an overall impression or relation between the various dimensions. This report uses spider charts for displaying the acceptable ranges of sensor metrics and attributes for a particular chemical and biological defense scenario.

By plotting the characteristics of a specific sensor on the spider chart, it is possible to quickly convey the acceptability of that sensor for a given defense scenario and to evaluate whether the sensor characteristics are balanced. Figure I shows a spider

chart for Scenario 3, Ground Forces Defense. This spider chart contains 11 radial legs that represent the four key important sensor metrics (shown in red) plus the seven other sensor attributes. Surrounding this title are three concentric rings. These rings represent different levels of acceptability for each metric or attribute. The inner ring indicates the marginally acceptable or threshold value, the middle ring indicates the nominal value, and the outer ring indicates the point of diminishing return or diminishing return value. The marginally acceptable value sets the boundary for whether a sensor is useful. An acceptable sensor for a given scenario would have characteristic values that are greater than the inner ring for all the spider legs. A sensor is not useful for the given scenario if it has any value that is inside the inner ring. The nominal value provides adequate performance for the scenario. The diminishing return value is that value for which further improvements do not generate significant operational capability enhancements. For each of the scenarios considered, a determination of the values for the inner, middle, and outer ring was made by a combination of quantitative analysis and informed estimation.

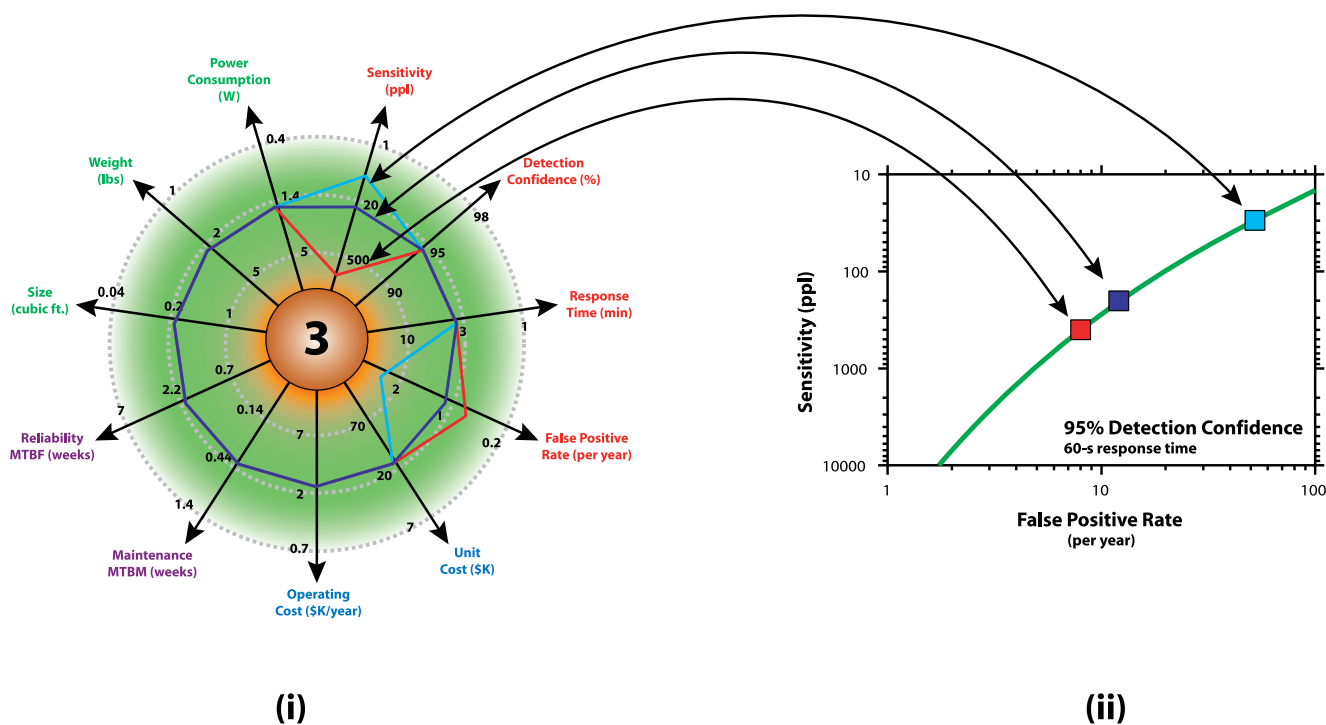


Figure I. (i) Plot of the key metrics and other attributes of a fictitious biological agent sensor on the “ground forces defense” spider chart. (ii) Sensor receiver operating characteristic (ROC) curve illustrating how different points on the ROC curve translate to different spider plot curves.

Sensor requirements are dependent upon their operational context. In order to help guide the sensor development community, a diverse set of scenarios are needed that describe the operational context in which the sensors will be used along with the corresponding sensor requirements. Table I lists the 14 scenarios developed by the panel.¹ It should be stressed that the objective of the panel was not to develop an exhaustive list of possible mission scenarios, but rather a practical number of scenarios that covers a reasonable amount of the threat space. Also, the scenarios were restricted to detect-to-warn strategies using point sensors of aerosol and vapor threats. For each scenario, a description is provided along with the scenario details, results of the multirealization analysis, and the corresponding spider chart. The definitions of the scenario details and multirealization analysis terms are described, by way of example, in Table II. Tables similar to Table II are constructed for each of the 14 scenarios and are described in detail in the main body of this report.

Footnotes

¹ The Panel was composed of respected scientific and technical subject matter experts from Defense Advanced Research Projects Agency, Massachusetts Institute of Technology Lincoln Laboratory, Defense Threat Reduction Agency, Office of the Secretary of Defense, Booz Allen Hamilton, Pacific Northwest National Laboratories, Research, Development, and Engineering Command, US Naval Research Laboratory, and the US Army Research Laboratory.

It is important to acknowledge that there is little guidance about the exact nature of possible chemical and biological attacks that sensors aim to detect. In order to determine the spider chart marginal, nominal, and diminishing return values, a multirealization analysis was conducted for each of the 14 scenarios. The output of the simulation provides a range of values (from marginally acceptable to diminishing return) for three specific attributes: sensitivity, response time, and sensor spacing. A key conclusion of this analysis is that those scenarios in which the enemy releases the agent along a line, and thereby creates a very large plume, require the most sensitive sensors. However, these sensors can be sparsely deployed. In contrast, scenarios in which the enemy releases the agent from a single point do not require very sensitive sensors, but those sensors must be deployed with a high density. Clearly, scenarios in which the enemy releases the agent in very close proximity to friendly troops require fast sensor response time as do scenarios where operational considerations require the sensors to be deployed very close to the defended troops.

Scenario Details		Spider Chart																								
Agent	Bacillus anthracis (anthrax)	<table border="1"><caption>Spider Chart Data</caption><thead><tr><th>Metric</th><th>Value</th></tr></thead><tbody><tr><td>Sensitivity (ppl)</td><td>1</td></tr><tr><td>Detection Confidence (%)</td><td>98</td></tr><tr><td>Response Time (min)</td><td>1</td></tr><tr><td>False Positive Rate (per year)</td><td>0.04</td></tr><tr><td>Unit Cost (\$K)</td><td>0.25</td></tr><tr><td>Operating Cost (\$K/year)</td><td>0</td></tr><tr><td>Maintenance MTBM (weeks)</td><td>NA</td></tr><tr><td>Reliability MTBF (weeks)</td><td>NA</td></tr><tr><td>Size (cubic ft.)</td><td>0.04</td></tr><tr><td>Weight (lbs)</td><td>1</td></tr><tr><td>Power Consumption (W)</td><td>0.1</td></tr></tbody></table>	Metric	Value	Sensitivity (ppl)	1	Detection Confidence (%)	98	Response Time (min)	1	False Positive Rate (per year)	0.04	Unit Cost (\$K)	0.25	Operating Cost (\$K/year)	0	Maintenance MTBM (weeks)	NA	Reliability MTBF (weeks)	NA	Size (cubic ft.)	0.04	Weight (lbs)	1	Power Consumption (W)	0.1
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Weight (lbs)	1																									
Power Consumption (W)	0.1																									
Release Information	Single point release ground level stationary sprayer																									
Area of Operation	Main supply route (MSR)																									
Personnel Involved	Military combat brigade																									
Duration of sensor operation required	1 hour x 10 convoys x 7 days = 70 hours																									
Realization Scenario Analysis																										
Sensitivity (ppl)	Spacing (meters)	Response Time (minutes)																								
1 – 500	50 – 500	1 – 10																								

Table II. Convoy movement scenario specifications and spider chart.

It is noteworthy that the false positive rate is not a quantitative output of the multirealization simulation. While the false positive rate is one of the key metrics of a sensor, it generally receives the least amount of analysis owing to the complexity of the calculation. Generally, the acceptable false positive rate is determined by surmising what the users will tolerate. An attempt was made to bound the acceptable false positive rate for each scenario by comparing the risks and costs associated with using agent sensors versus not using agent sensors. Although this analysis is largely based on the informed estimation of an experienced study panel, Appendix 2 presents a description of a process for providing a more analytical estimate of the acceptable false positive rate. The detailed results of this analysis are classified and, therefore, are not presented here.

Finally, the Phase II Study report describes a path forward to examine several other critical issues not covered to date. These topics are listed below, and described more fully in Section 7.0 of this report.

- Standoff Sensors
- Confirmatory Sensors (or “Identifiers”)
- Networking of Sensors
- Sample Collectors
- Scenario “Degradation”
- Quantitative Analysis

The specific accomplishments of the Phase II Study are summarized below:

1. Developed fourteen chemical and biological attack scenarios for the purpose of evaluating sensor requirements.
2. Conducted a multirealization mathematical analysis in order to quantitatively determine the sensor requirements for sensitivity, response time, and deployment density for each scenario.
3. Conducted a quantitative cost-benefit analysis in order to determine the false positive rate requirements for two scenarios.
4. Constructed sensor requirement spider charts for each scenario that detail the minimally acceptable, nominal, and diminishing return values for the sensor key metrics as well as the other sensor attributes.



1.0 BACKGROUND

The evaluation of chemical and biological (CB) sensors does not fully meet the needs of the operational community. Limitations include not only the evaluation of sensor performance metrics but also the evaluation of sensor requirements. In August 2003, the Defense Advanced Research Projects Agency (DARPA) initiated the Chemical and Biological Sensor Standards Study (CBS3) to investigate the evaluation of CB sensors. At that time there were no sound methods or metrics to evaluate the performance of a sensor or to compare like sensors. Phase I of this study was primarily concerned with the evaluation of sensor performance metrics. The results of Phase I were published by DARPA in August of 2004, and since its distribution, the findings in the Phase I report have shifted the CB community perspective and approach in reporting sensor performance metrics. The present report is the result of Phase II of this study and is primarily concerned with the evaluation of sensor requirements.

To address the inadequate evaluation of sensor performance metrics, Phase I of the study proposed that the performance of a CB agent sensor is most properly characterized by four key sensor metrics and several other important sensor attributes (Table 1.1). The key sensor metrics are closely related to each other and this relationship is captured in the receiver operating characteristic (ROC) curve. By specifying the sensitivity of a sensor system, there is an

implicit associated detection confidence and false positive rate as dictated by the ROC curve. It is meaningless to specify sensitivity without indicating the probability of detection and false positive rate. The sensor sensitivity, detection confidence, false positive rate, and response time are all related and all depend on the sensor's operating environment. The ROC curve will generally depend on the environment in which the sensitivity and false positive rates are measured. More complex environments will usually produce higher false positive rates at a given sensitivity than less complex environments (Figure 1.1).

Key Metrics	Other Attributes
Sensitivity	Unit Cost
Probability of Detection	Operation Cost
False Positive Rate	Maintenance (MTBM)
Response Time	Reliability (MTBF)
	Size
	Weight
	Power Consumption

MTBM – Mean time between maintenance

MTBF – Mean time between failures

Table 1.1 Key sensor metrics as proposed in Phase I and other sensor attributes as modified in Phase II.

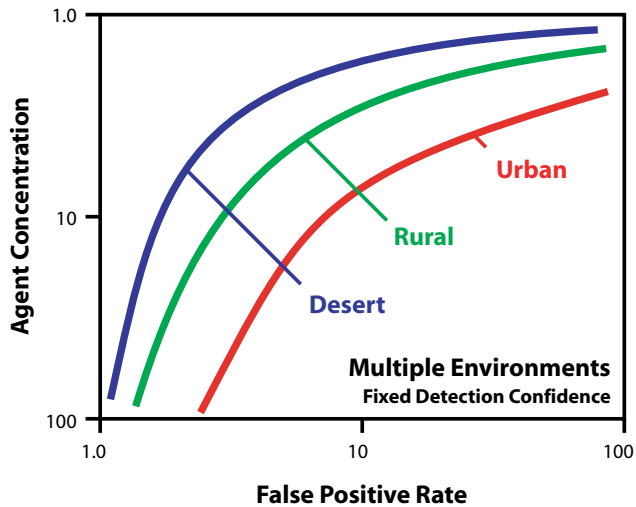


Figure 1.1 Three notional sensor receiver operating characteristic (ROC) curves for different environments in which a sensor is operated. For each curve the detection confidence and response time are fixed.

The Phase I report proposed that ROC curves should be used for the evaluation of CB sensors and described how to generate these curves. In addition, the Phase I report utilized four single-realization CB defense scenarios to illustrate the process of determining the appropriate ranges of sensor requirements. A single-realization scenario employs a specific set of agent release conditions (for example, mass, distance, wind speed, and wind direction). The analysis of these four scenarios showed that different scenarios may require very different levels of sensor performance.

Phase II of this study was initiated by DARPA and completed by DTRA to ascertain and evaluate sensor requirements based on sensor performance metrics. The scope and validity in determining sensor requirements was expanded through refining the use of Spider Charts to display sensor requirements and characteristics through the development of 14 multirealization scenarios. Further, a multivariate methodology was developed and utilized to determine the requirements of CB sensors for each of the 14 operational scenarios.

The CBS3 Phase I study identified five key findings:

1. The potential agent threat spans a dynamic concentration range greater than 10^6 .
2. Requirements for sensors are not well defined.
3. Receiver operating characteristic (ROC) curves are essential for the development, testing, and evaluation of CB sensors.
4. Sensors must allow for multiple operating modes allowing for adjustment of sensitivity and false positive rate to meet operational requirements.
5. CB sensor testing and characterization is outdated and inadequate.

The Phase I report details these findings and made subsequent recommendations.



2.0 INTRODUCTION

This report details the development of a methodology for determining the requirements of chemical and biological sensors. The methodology involves the use of multirealization scenario analysis. In contrast to a single realization scenario, as employed in Phase I, a multirealization scenario utilizes a range of agent release characteristics. For example, the release mass, release distance, and wind conditions are allowed to vary over a range of values within the scenario. While more difficult to analyze, multirealization scenarios make fewer assumptions about the attack characteristics. Since the attacker will control the nature and conditions of the attack, a sound requirement will be based on the range of possible attacks. Thus, multirealization scenarios form a better basis for requirements definition than do single realization scenarios.

To aid in the multivariate analysis, the Hazard Prediction and Assessment Capability⁴ (HPAC) computer software was used to analyze agent transport and its statistical variation. While the statistics of HPAC are not commonly utilized, this information is quite important when generating sensor requirements. For example, HPAC may report that a particular agent release produces low agent concentrations at a particular position. A sensible conclusion would be that a sensor placed at that position must be sensitive to low agent concentration. However, further investigation of the HPAC statistics may show that the low concentration is a result of an average of many instances in which no agent was present and a few instances in which a high agent

concentration was present. This additional information drastically changes the sensor requirements.

Sensor requirements are dependent upon their operational context. In order to help guide the sensor development community, a diverse set of scenarios are needed that describe the operational context in which the sensors will be used along with the corresponding CB sensor requirements. To generate the CB sensor requirements, 14 multirealization CB defense scenarios were developed and analyzed by the multivariate methodology. While clearly not intended to be exhaustive, these scenarios represent plausible CB attacks on the major branches of the US military and cover a wide range of conditions including outdoors, indoors, permanent fixed sites, temporary fixed sites, moving operations, CB agents, single point releases, multiple point releases, and line releases. However, the scenarios were restricted to detect-to-warn strategies using point sensors of aerosol and vapor threats. The 14 scenarios developed are listed in Table 2.1.

In this study, a parallel approach was taken to generate the acceptable sensor metric ranges on the spider chart for each scenario. This was accomplished by developing a diverse set of scenarios that describe the operational context by which sensors will be used and then inputting the parameters for each scenario into an analysis. To obtain the sensitivity and response time key sensor metric axes, as well as the sensor density for each scenario, parameters

Footnotes

⁴ PC-SCIPUFF Technical Documentation, R.I. Sykes, S.F. Parker, D.S. Henn, C.P. Cerasoli, L.P. Santos, Titan Corporation, Titan Research and Technology Division, P.O. Box 2229, Princeton, New Jersey, September 1998. Support for the implementation of the SCIPUFF algorithms in the HPAC program was provided by the Defense Threat Reduction Agency, Collateral Effects Section.

were placed into the multirealization analysis. This analysis serves as a methodology that can be followed by varying the input parameters for each scenario. In parallel, the panel also evaluated each scenario and agreed upon reasonable ranges for false positive rate and other sensor attributes. Figure 2.1 illustrates the approach taken in this study.

The rest of the report is organized as follows:

Scenario		Agent	Release Type	Release Comments
1	Convoy Movement	Anthrax	Single Point	Stationary sprayer
2	Convoy Movement	Sarin	Single Point	Stationary sprayer
3	Ground Forces Defense	Anthrax	Single Point	Stationary sprayer
4	Military Building (internal attack)	Smallpox	Single Point	Slow release from box
5	Military Building (external attack)	TIC	Single Point	Tanker truck release
6	Amphibious Operation	Mustard	Multiple Point	Mines
7	OCONUS Forward Airbase	VX	Multiple Point	Missile air bursts
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10	CONUS Military Post	Anthrax	Line	Aircraft sprayer
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12	Defensive Positions	Anthrax	Line	Aircraft sprayer
13	Naval Port Facility	Anthrax	Line	Moving truck with sprayer
14	Navy Ship in Littoral	Plague	Line	Small boat with sprayer

OCONUS – Outside Continental United States

CONUS – Continental United States

TIC – Toxic Industrial Chemical

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Table 2.1 Scenarios utilized to generate CB agent sensor requirements.

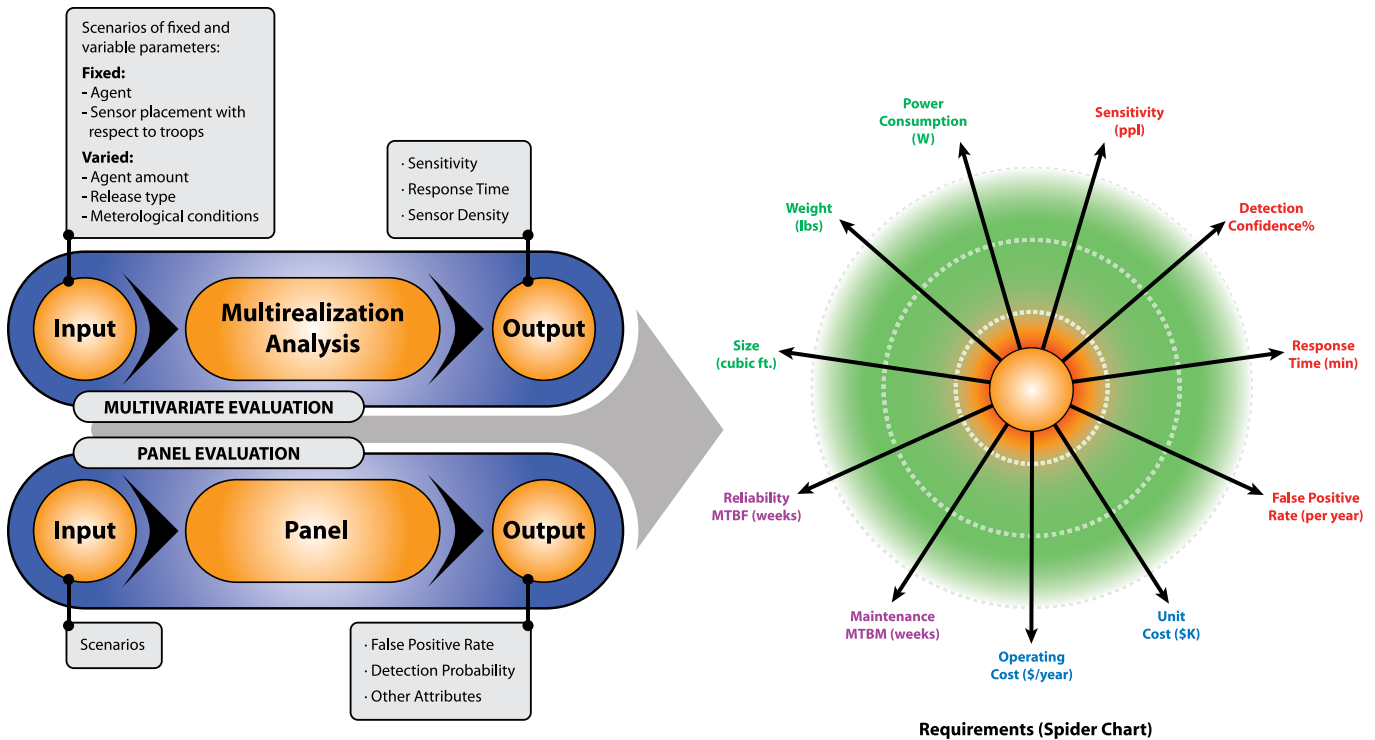


Figure 2.1 Approach utilized in this study.

- Section 3.0 describes the construction of spider charts and the relation of ROC curves to spider charts;
- Section 4.0 describes the multirealization analysis process and how sensor requirements were determined for corresponding scenarios;
- Section 5.0 details the 14 scenarios and associated spider charts;
- Section 6.0 summarizes the findings and conclusions made in this report; and
- Section 7.0 details a path forward for this and other future studies.

The specific accomplishments of the Phase II Study are summarized below:

1. Developed fourteen chemical and biological attack scenarios for the purpose of evaluating sensor requirements.
2. Conducted a multirealization mathematical analysis in order to quantitatively determine the sensor requirements for sensitivity, response time, and deployment density for each scenario.
3. Conducted a quantitative cost-benefit analysis in order to determine the false positive rate requirements for two scenarios.
4. Constructed sensor requirement spider charts for each scenario that detail the minimally acceptable, nominal, and diminishing return values for the sensor key metrics as well as the other sensor attributes.



3.0 SPIDER CHARTS

This report uses spider charts for displaying the acceptable ranges of sensor metrics and attributes for a particular chemical and biological defense scenario. By plotting the characteristics of a specific sensor on the spider chart, it is possible to quickly convey the acceptability of that sensor in a given defense scenario and to evaluate whether the sensor characteristics are balanced. Figure 3.1 shows a spider chart for Scenario 3, Ground Forces Defense (see inset for scenario details). This spider chart contains 11 radial legs that represent the four key sensor metrics plus the seven other sensor attributes. The center of the spider chart contains the scenario number. Surrounding this number

are three concentric rings which represent different levels of acceptability for each metric or attribute. The inner ring indicates the marginally acceptable or threshold value, the middle ring indicates the nominal value, and the outer ring indicates the diminishing return value. The marginally acceptable value sets the boundary for whether a sensor is useful. An acceptable sensor for a given scenario would have characteristic values that are greater than the inner ring for all the spider legs. A sensor is not useful for the given scenario if it has any value that is inside the inner ring. The nominal value provides adequate performance for the scenario. The diminishing return value is that value for which further improvements do not generate significant operational capability enhancements. A sensor that has a value, along any spider leg, outside of the outer ring (objective value) is performing better than is needed for that particular metric.

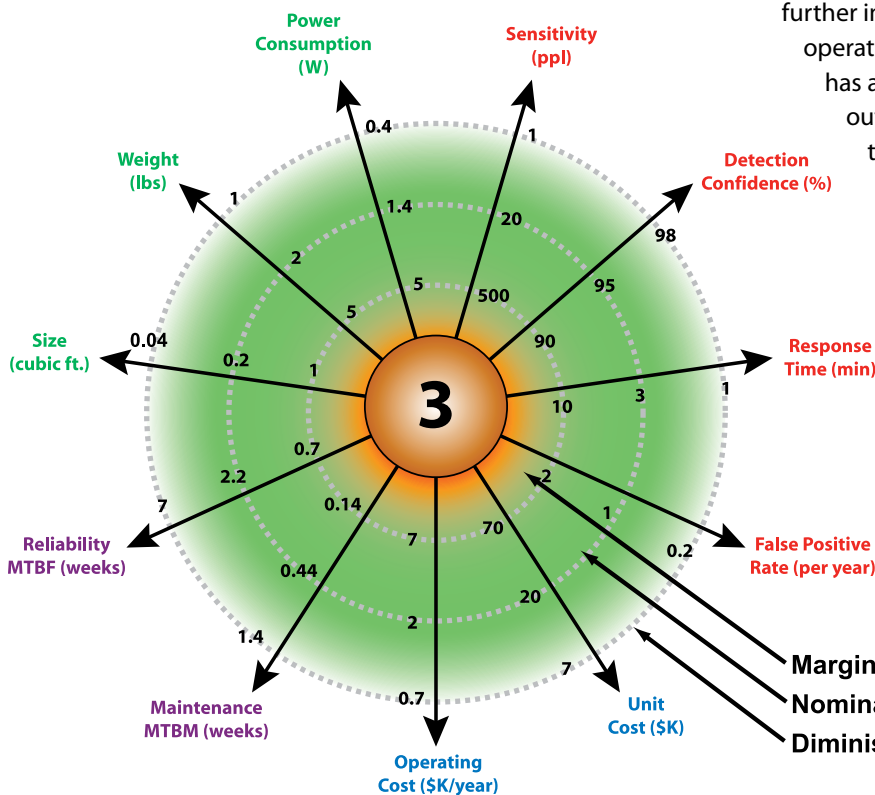


Figure 3.1 The spider chart shows four key performance metric legs and seven other attribute legs. The ground forces defense (Scenario 3) spider chart shows that the marginal sensitivity is 500 particles per liter (ppl) of air, with little additional benefit in having a sensor with sensitivity of better than 1 ppl. Similarly, the largest acceptable sensor volume is 1 cubic foot, with little benefit in reducing this volume below 0.04 cubic feet.

Marginal (Threshold) Value
Nominal Value
Diminishing Return (Objective) Value

For each of the scenarios considered, a determination of the values for the inner, middle, and outer ring was made by a combination of quantitative analysis and informed estimation by the Study Panel. The values for the sensitivity and response time vectors were determined by the multirealization scenario analysis described in Section 4.0 and Appendix I. The detection confidence values (90, 95, and 98 percent) were chosen to be the same for all the scenarios. For two scenarios (2 and 11), the false positive rate values were determined by the analysis described in Appendix II. The false positive rate values for the other scenarios are estimates of the panel. In addition, the other attribute values for each scenario are also estimates of the panel. It is recognized that there are likely differing opinions about the proper ring values along each spider leg, especially for the legs that are determined by estimation.

Figure 3.2 expands on Figure 3.1 and illustrates how the key metrics and other attributes of a fictitious biological agent sensor are represented on the spider chart for a ground forces defense scenario. This sensor has a default configuration in which its key metrics and other attributes

are equal to the nominal values of the spider chart, as shown by the purple line. However, as discussed in the Phase I report, it is possible to adjust the key sensor metrics so as to improve some of these metrics relative to others. For example, by adjusting the sensitivity threshold to obtain the marginally acceptable sensitivity, the false positive rate can be reduced (red square and red line in Figure 3.2). Similarly, by reducing the detection threshold, the sensor sensitivity can be improved but at the cost of an increased false positive rate (light blue square and light blue line in Figure 3.2).

It is also possible to adjust the detection confidence or the response time and thereby shift the sensor ROC curve in Figure 3.2 (b). For example, by reducing the detection confidence, the sensitivity can be improved without affecting the false positive rate. A sensor will have a variety of spider chart patterns for a given scenario, depending upon where it is operated on its ROC curve. It may also be possible that some of the other attributes can be traded off against one another to change the spider chart pattern so as to favor some attributes over others.

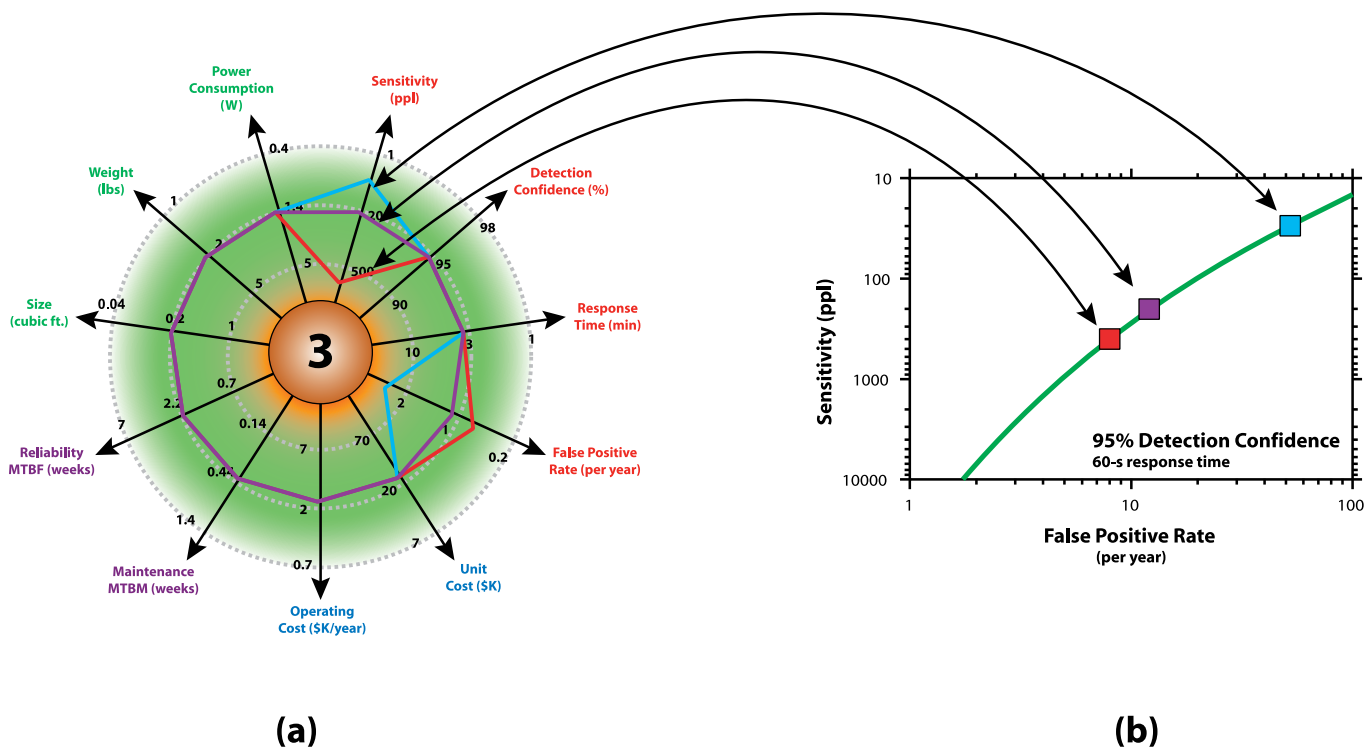


Figure 3.2. (a) Plot of the key metrics and other attributes of a fictitious biological agent sensor on the ground forces defense spider chart. (b) The corresponding sensor ROC curve illustrating how different points on the ROC curve translate to different spider plot curves.

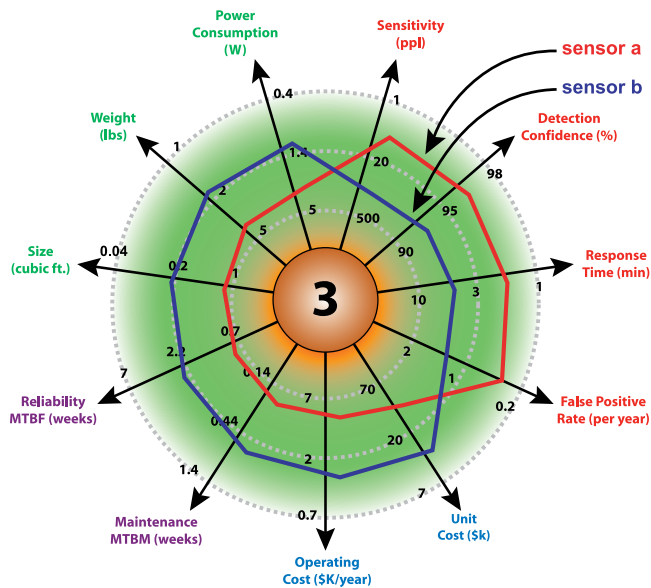


Figure 3.3 Spider chart illustrating the relative balance between the key metrics and other attributes for two fictitious sensors.

The spider chart can also be used to evaluate the balance among the key sensor metrics and other attributes. Figure 3.3 illustrates the performance of two fictitious biological agent sensors. Each sensor is acceptable for this scenario. Sensor “a” has better key metrics but other attributes that are worse than sensor “b.” Dependent upon the user’s preference, the sensor plots imply that sensor “a” could sacrifice the key metrics in order to achieve better other attributes while sensor “b” would benefit from just the opposite.

Scenario Details	
Defense Posture	
Agent of Operation	U.S. combat forces defensive position
Personnel Involved	2 – 3 battalions
Sensor Positions	Between enemy and US forces
Sensor To Protected Area Distance	1.5 - 4 km
Sensor Mission Duration	24 hours
Protective Response Time	2 min
Attack Parameters	
Agent	<i>Bacillus anthracis</i> (anthrax)
Release Type	Single point release from ground level stationary sprayer
Release Mass	20 g – 1 kg
Release Distance From Sensors	0.5 - 8 km
Multirealization Scenario Analysis	
Sensor Sensitivity	1 – 500 ppl
Sensor Spacing	50 – 100 meters
Sensor Response Time	1 – 10 min





4.0 ANALYTICAL METHODOLOGIES

The panel developed 14 scenarios covering a range of operational situations. The scenarios were used to develop requirements for sensors. The detailed nature of potential chemical or biological attacks is difficult to predict and the Panel was required to make several assumptions about the details of such attacks within the scenarios. These assumptions (e.g. specific agents, specific means of dissemination, dissemination durations) served as inputs to a multirealization analysis of each scenario. Multirealization analyses employ a range of agent release characteristics (e.g. agent quantity, wind speed, upwind attack distance). Figure 4.1 illustrates the approach taken for this study.

These assumptions were necessary inputs in order to conduct a multirealization analysis for each scenario discussed in the next section. Multirealization analyses employ a range of agent release characteristics and provide the decision maker with a more robust set of sensor requirements. In this analysis, a range of agent release masses was allowed to occur at a variety of different locations and under a variety of different environmental conditions within the scenario. This analysis in turn forms the basis for determining the spider chart marginal, nominal, and diminishing return values by generating outputs for the sensitivity and response time, both key metric axes of the spider chart. Further, multirealization analyses generate the required sensor density needed to detect an attack, which in turn affects the cost axes of the spider charts.

Note that the false positive rate is not a quantitative output of this analysis. While the false positive rate is one of the key metrics of a sensor, it generally receives the least amount of analysis because of the complexity of the calculation.

Generally, acceptable false positive rates are determined by estimating what users will tolerate. An attempt was made to bound the acceptable false positive rate for each scenario by comparing the risks and costs associated with using versus not using agent sensors. While this analysis is largely based on the informed estimation of an experienced study panel, Appendix 2 presents a description of the process for providing a more analytical estimate. This process was used for scenarios 2 and 11.

Table 4.1 summarizes the results of the multirealization analysis for all 14 scenarios. The analysis shows that there are wide ranges for the acceptable sensitivity, response time, and sensor spacing. In some cases, the range spans a factor of one thousand. Scenarios in which the enemy releases the agent along a line, creating a very large plume, require the most sensitive sensors, though these sensors can be sparsely deployed. In contrast, scenarios in which the enemy releases agent from a single point do not require very sensitive sensors, though they must be deployed with a high density. Clearly, scenarios in which the enemy releases the agent in very close proximity to friendly troops require fast sensor response time. In some cases there is not enough time between the agent release or agent arrival at the sensors and its arrival at friendly troops to provide adequate warning even if the sensors respond instantaneously. In these cases the sensors provide a detect-to-treat function.

It should be noted that the zeroes in the reaction time column for several scenarios signify that at some wind speeds the plume moves from the sensors to at least some of the protected troops faster than the two minutes that is assumed for troops to don personal protective equipment (PPE). In these cases, sensors that have response times

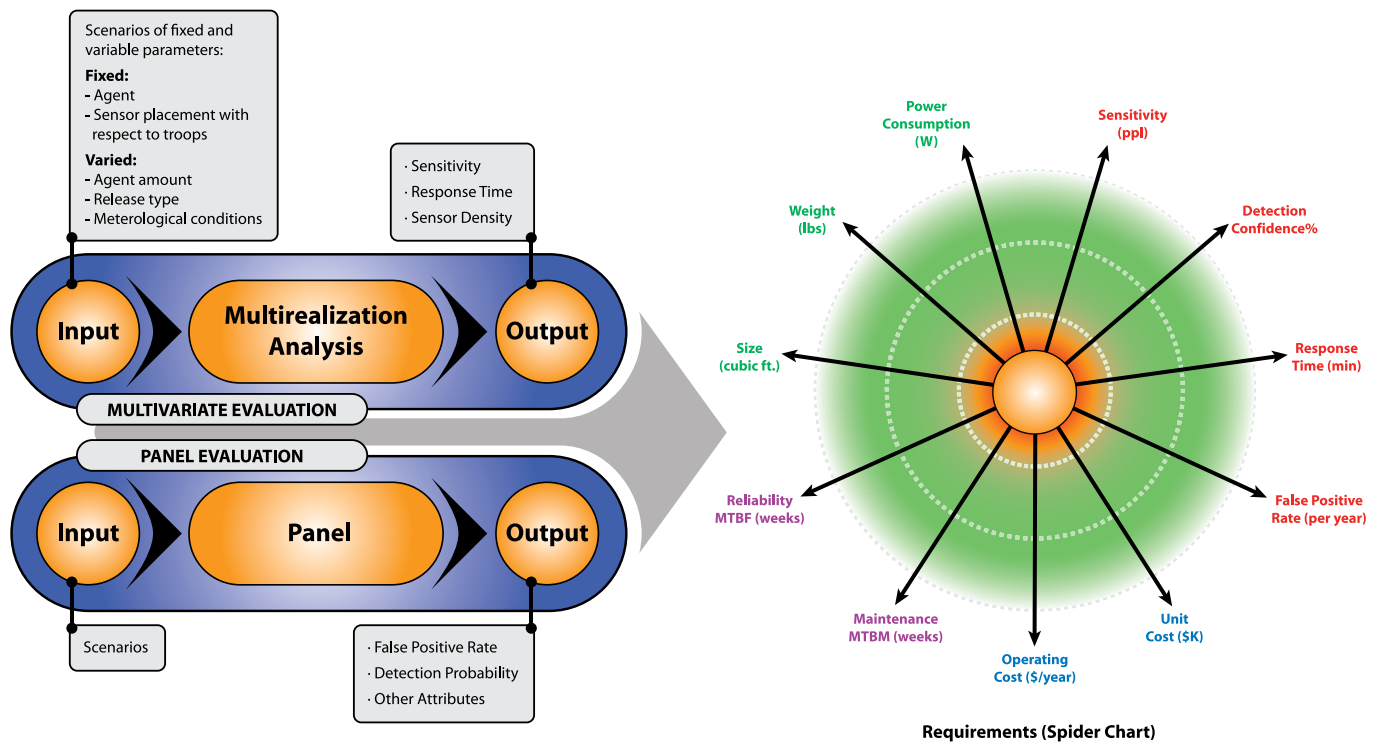


Figure 4.1 Approach utilized in this study.

	Scenario	Agent	Sensor Sensitivity	Sensor Reaction Time (minutes)	Sensor Spacing (m)
1	Convoy Movement	Anthrax	1 – 500 ppl	1 – 10	50 – 500
2	Convoy Movement	Sarin	0.1 – 10 mg/m ³	1 – 10	50 – 100
3	Ground Forces Defense	Anthrax	1 – 500 ppl	1 – 10	50 – 100
4	Military Building (internal attack)	Smallpox	0.1 – 100 ppl	1 – 1	One per air duct
5	Military Building (external attack)	TIC	0.5 – 500 mg/m ³	0.1 – 1	One on roof
6	Amphibious Operation	Mustard	0.1 – 1 mg/m ³	1 – 30	500 - 100
7	OCONUS Forward Airbase	VX	0.01 – 2 mg/m ³	0 – 3	25 – 100
8	Terrain Denial	VX	0.1 - 10 mg/m ³	0 – 3	1 sensor per lead vehicle
9	CONUS Military Post	Anthrax	0.1 – 1 ppl	0 – 10	50 – 100
10	CONUS Military Post	Anthrax	0.1 – 25 ppl	1 – 7	500 – 1,000
11	Defensive Positions	Sarin	0.1 – 2 mg/m ³	1 – 6	500 – 1,000
12	Defensive Positions	Anthrax	0.1 – 10 ppl	0 – 2	500 – 1,000
13	Naval Port Facility	Anthrax	1 – 500 ppl	0 – 7	10 sensors on perimeter
14	Navy Ship in Littoral	Plague	1 – 500 ppl	0 – 0.25	10 sensors on deck

OCONUS – Outside Continental United States

CONUS – Continental United States

TIC – Toxic Industrial Chemical

VX and Sarin – Common names for two toxic chemicals

Table 4.1 Results of multirealization analysis for each scenario. (The military building analysis results (4 & 5) were provided by Alex Metrovich, Anser Inc.)

down to zero seconds (i.e. immediate detection) generate significant protective benefit. A detailed discussion of this concept is provided in Section 4.3.

Multirealization Analysis

As noted in Section 4.0, in order to perform the multirealization analysis for each scenario, the range of agent release characteristics had to be defined. For each scenario a general release type is chosen; the release mass, location and the environmental conditions are varied. The three types of releases utilized in this analysis are:

- Single point release
- Multiple point release
- Line release

Historical data from the regions of interest was used to define the range of wind speeds. Release locations were varied to represent a range of conditions that are reasonable for the expected operational situation in each scenario. Specifically, releases are expected to occur in places where the agent is likely to reach the target troops.

The detectable agent release masses are compared with those agent masses that can plausibly be expected for each scenario. The plausible release masses are bounded above either by the amount of agent an enemy is likely to utilize without attracting undesirable attention or by the amount that can be readily disseminated by the dispensing mechanism described in the scenario. The plausible release masses are bounded below, either by the amount of agent that is too small to have the desired effect on the target troops or by an amount that is too small to be readily handled in the proposed dispensing mechanism. For example, in scenarios using backpack sprayers, it is assumed that no more than 10 kilograms of agent will fit in the individual sprayer. Conversely, with less than 10 grams of agent, the attacker would choose a less obtrusive dissemination method. The cost of production of the agent and the complexity of the process were also taken into account.

The analysis was made based on the utilization of an array of sensors rather than a single sensor because this represents the most likely sensor deployment configuration for the scenarios. For the purposes of this report and subsequent analysis, the individual sensor detection probability, as

specified in the spider chart, is the probability that the sensor will alarm given that the concentration in the plume has exceeded the sensor's threshold concentration. In contrast, the array detection probability is the probability that the concentration in the plume will exceed the detection threshold for at least one sensor in the array. In this analysis, a fixed spacing of sensors was chosen and was then varied until the sensor density reached a point of diminishing return. Specifically, the sensor density would acceptably guarantee that one sensor in the array would detect the concentration of the plume for the sensor detection threshold within the constraints of the release mass and wind speed.

To calculate the joint probability of exceeding the concentration detection threshold for at least one of the sensors within an array, three methods were considered: Largest Individual Detection Probability, Uncorrelated Concentration, and Correlated Concentration. Employing the Largest Individual Detection Probability method overestimates the sensor sensitivity requirements. Conversely, applying the Uncorrelated Concentration method underestimates the sensor sensitivity requirements. Therefore, the Correlated Concentration method was chosen as it provided the most realistic estimate of detection probability for sensor requirements. Further description of each method considered can be found in the inset titled "Calculating Joint Probability."

To generate and model a released agent plume, the Hazard Prediction and Assessment Capability⁶ (HPAC) software was chosen. HPAC agent models are well understood and prove to be an adequate solution in generating the outputs needed for this analysis.

For each release condition, HPAC was used to calculate the statistical characteristics of the spatial and temporal concentration of the released agent plume. This plume is then used to challenge an array of sensors whose individual detection threshold and spatial density are varied. For each release condition and sensor array density, the release mass that can be detected with a 95 percent probability is calculated. This 95 percent detection probability represents an array detection probability and not an individual sensor detection probability. For the purpose of this analysis, it is assumed that when the agent concentration within the plume exceeds the individual sensor's detection threshold (or sensitivity axis on the spider chart) the individual sensor

Footnotes

⁶ PC-SCIPUFF Technical Documentation, R.I. Sykes, S.F. Parker, D.S. Henn, C.P. Cerasoli, L.P. Santos, Titan Corporation, Titan Research and Technology Division, P.O. Box 2229, Princeton, New Jersey, September 1998. Support for the implementation of the SCIPUFF algorithms in the HPAC program was provided by the Defense Threat Reduction Agency, Collateral Effects Section.

Calculating Joint Probability

1. Largest Individual Detection Probability – Uses the largest individual probability of the concentration exceeding the detection threshold for any sensor in the array. For many scenarios, this largest detection probability will tend to be low. In order to raise the detection probability equal to or greater than 95 percent, the concentration detection threshold will have to be lowered (greater sensitivity). This case results in over specifying sensor sensitivity requirements.

For example, imagine 10 sensors each with a 50 percent probability of detecting the cloud. The probability that at least one sensor detects the cloud is greater than 50 percent. This fact, however, is ignored. Instead greater sensitivity for all of the sensors is forced until at least one of the sensors record a 95 percent detection probability.

2. Uncorrelated Concentration – Assumes that all the agent concentrations at all sensors are independent and uses the combined probabilities of each of the sensors to determine the overall probability of detecting the agent cloud. This case results in the most optimistic estimate of detection probability and results in under-specifying sensor requirements.

Again, imagine 10 sensors that each have a 50 percent probability of detecting the cloud. If these detection probabilities were independent, then the probability of at least one sensor detecting the cloud would be nearly equal to 100 percent. Similarly, if each sensor had a 26 percent detection probability then the array of sensors would achieve overall 95 percent detection probability. In the last case, the calculation for the ten independent sensors is $(1 - (1-0.26)^{10}) = 0.95$.

3. Correlated Concentration – Computes the joint probability of detection based on the assumption of an exponentially decaying correlation concentration function with a correlation scale length L . This case is the most realistic; however, it is difficult to evaluate the correlation scale length precisely. The results are not overly sensitive to the value of L as long as it is comparable to scale lengths of the mean horizontal turbulence.

will, detect that agent with 100 percent probability. The algorithm for calculating the joint probability of detection was chosen with some care. As explained in the following summary box, Calculating Joint Probability, it is easy to underestimate or to overestimate the likelihood of success. The correct approach is defined by Algorithm 3, Correlated Concentration. Algorithm 3 was used to generate the results for this report.

Each sensor array is then evaluated using a range of attack parameters to which it is sufficiently sensitive to provide 95 percent probability of detection. The attack parameters varied in this analysis are:

- Agent release mass
- Release location
- Wind speed

Sensor sensitivity, response time, and physical spacing between sensors that allow detections of a small but not insignificant range of attack parameters are calculated for the inner ring on the spider chart. Exactly what is insignificant is a matter of engineering judgment. When further increases in sensitivity or density, or when decreases in response time do not significantly increase the range of attack parameters covered, the point of diminishing returns has been reached and the corresponding diminishing return values are determined for the outer ring on the spider chart. The overall approach is outlined in Figure 4.2.

HPAC Methodology

In order to illustrate how HPAC was used to ascertain the required multivariate analysis outputs, this section will use the Ground Forces Defense scenario (Section 5.0, scenario 3). Figure 4.3 reviews the specifications for the Ground Forces Defense scenario. The comprehensive mathematical details describing the process used by HPAC in this analysis are given in Appendix 1. The process allows one to determine the probability of an agent concentration exceeding the detection threshold for an array of sensors.

HPAC simulates the propagation of chemical or biological agents in the atmosphere and accounts for varying atmospheric stability and terrain roughness. The software employs spatially distributed agent plumes to represent the time-dependent concentration field in three spatial dimensions. The cloud of contaminants take the shape of an elongated plume of particles that move along a pathway downwind from the release location. Within the plume, natural turbulent eddies form taking the shape of transversely wide eddies with short downwind coverage at low wind speeds and transversely narrow eddies with long downwind coverage at high wind speeds. These turbulent eddies or individual realizations are characteristic of a plume traveling along a path. HPAC calculates the mean values for an ensemble of individual realizations yielding a Gaussian

plume, where maximum agent concentration would be in the center of the plume.

However, as shown in Figure 4.4, the temporal and spatial variation of the concentration differs significantly for an individual aerosol release (Figure 4.4 a-c) compared with the ensemble average (Figure 4.4 d). It is clear that turbulent agent transport is irregular and dependent upon the exact location and strength of the turbulent eddies. Thus, the probability of agent concentration exceeding a sensor detection threshold in an individual agent release cannot be calculated using only the ensemble average concentration from any such releases. That is, the probability of detection cannot be determined simply by comparing the mean concentration to the sensor detection threshold.⁷

In order to determine the probability of detection, a statistical measure of the expected variation between releases is also needed. HPAC provides these statistics and describes the spatial distribution of the agent by two time-dependent arrays of values for the mean and standard deviation of the concentration at any point within the spread of the airborne material. These statistics are used to determine the probability that the concentration of the agent exceeds a specified threshold at each point in time and space. HPAC statistics assume that the agent concentration at any point in space and time has a clipped

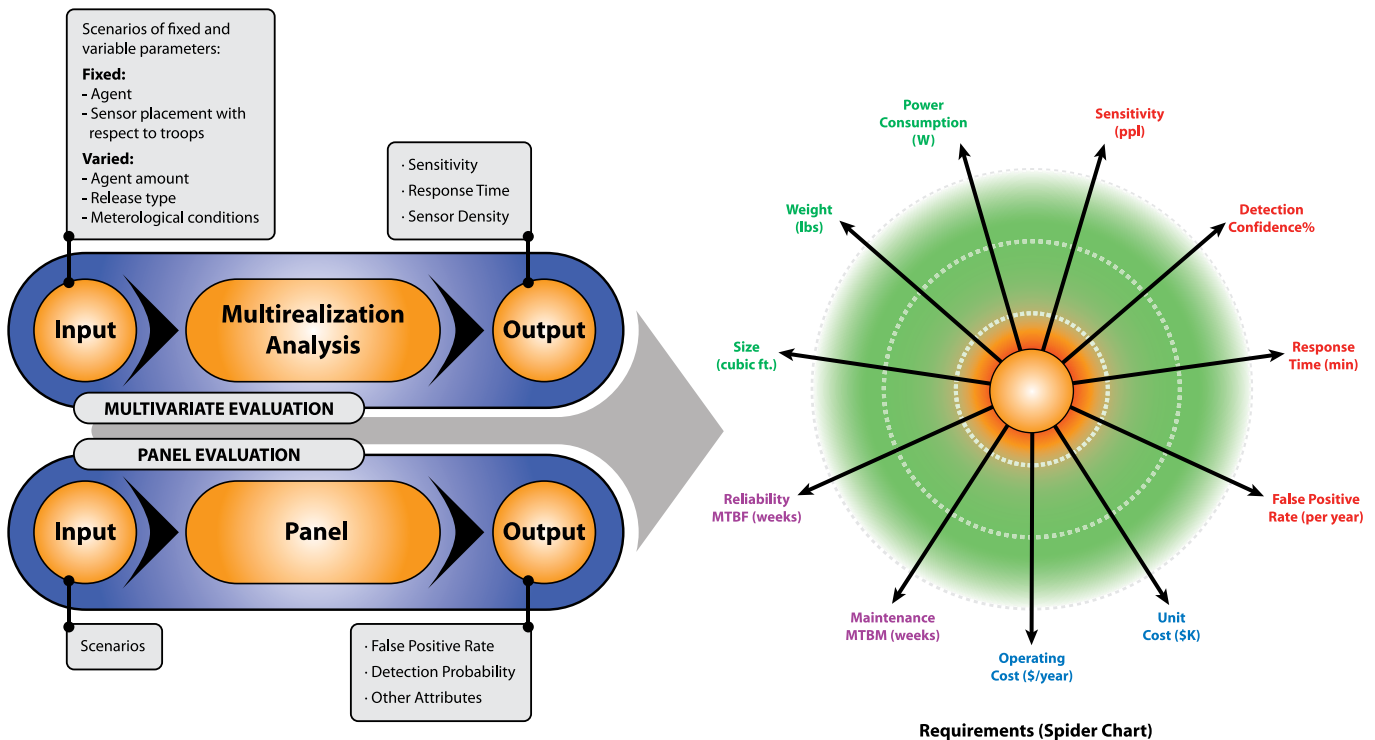


Figure 4.2 Overall approach taken during this study.

Scenario Details	
Defense Posture	
Agent of Operation	US combat forces defensive position
Personnel Involved	2 – 3 battalions
Sensor Positions	Between enemy and US forces
Sensor To Protected Area Distance	1.5 - 4 km
Sensor Mission Duration	24 hours
Protective Response Time	2 min
Attack Parameters	
Agent	<i>Bacillus anthracis</i> (anthrax)
Release Type	Single point release from ground level stationary sprayer
Release Mass	20 g – 1 kg
Release Distance From Sensors	0.5 - 8 km
Multirealization Scenario Analysis	
Sensor Sensitivity	1 – 500 ppl
Sensor Spacing	50 – 100 meters
Sensor Response Time	1 – 10 min

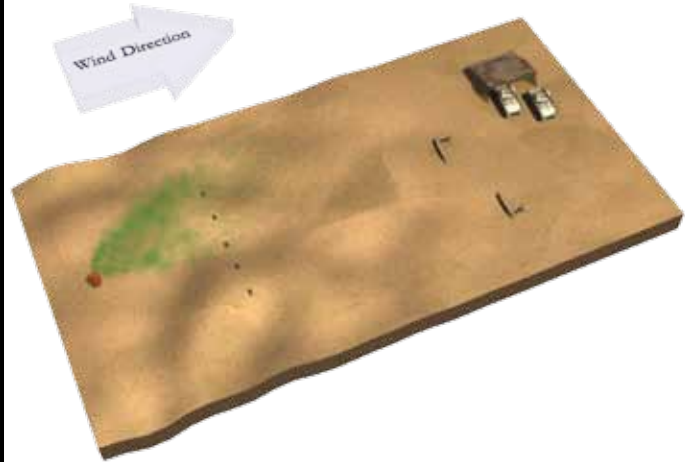


Figure 4.3 Illustration of the Ground Forces Defense scenario (Scenario 3). The multirealization analysis varies the amount of agent released, the distance behind the enemy/friendly boundary that the release occurs, and the environmental conditions (for example, wind speed, atmospheric stability).

Gaussian probability distribution function. As shown in Figure 4.5, a clipped Gaussian probability distribution function is an ordinary bell curve in which the negative portion of the curve is replaced with a delta function. The reason for this is that the negative portion of the curve in fact represents zero concentration within the plume.

The magnitude of the delta function is equal to the area under the clipped off portion of the curve (purple section in Figure 4.5) and represents the intermittency (I) of the probability distribution function for the concentration of the contaminant. In other words, the intermittency is the probability that no agent is present at that point in time and space.

The clipped Gaussian distribution function is used to calculate the probability that the concentration will exceed any given detection threshold at the corresponding point in time and space. As shown in Figure 4.5, the area under the curve to the right of a specified Sensor Threshold (T) is the probability that the concentration will exceed the threshold value T .

Using the release parameters in the Ground Forces Defense scenario (Scenario 3), Figure 4.6 shows a typical dosage profile generated by HPAC. In this scenario, *Bacillus anthracis* is released as an aerosol at the point marked by an "X" on the map. Winds carry the agent downwind (upward on the map) forming a plume. The beige color corresponds to the highest agent dosage, the red to the intermediate agent dosage, and the yellow to lowest agent dosage within the plume. Two points are plotted on the map, one on the left directly downwind from the release point in the highest concentration in the plume, and one on the right, on the edge of the plume at the lowest concentration in the plume. For each point, a graph of the corresponding probability density versus the time-dependent agent concentration are plotted. The point in the center of the plume experiences the highest agent concentrations and, as can be seen in Figure 4.6a, has a low intermittency ($I = 0.0042$) or low probability of zero agent concentration. In contrast, the point at the edge of the agent plume experiences the lowest agent concentration and, as can be seen in Figure 4.6b, has a high intermittency ($I=0.9885$) or high probability of zero agent concentration. In other words, at that point of time

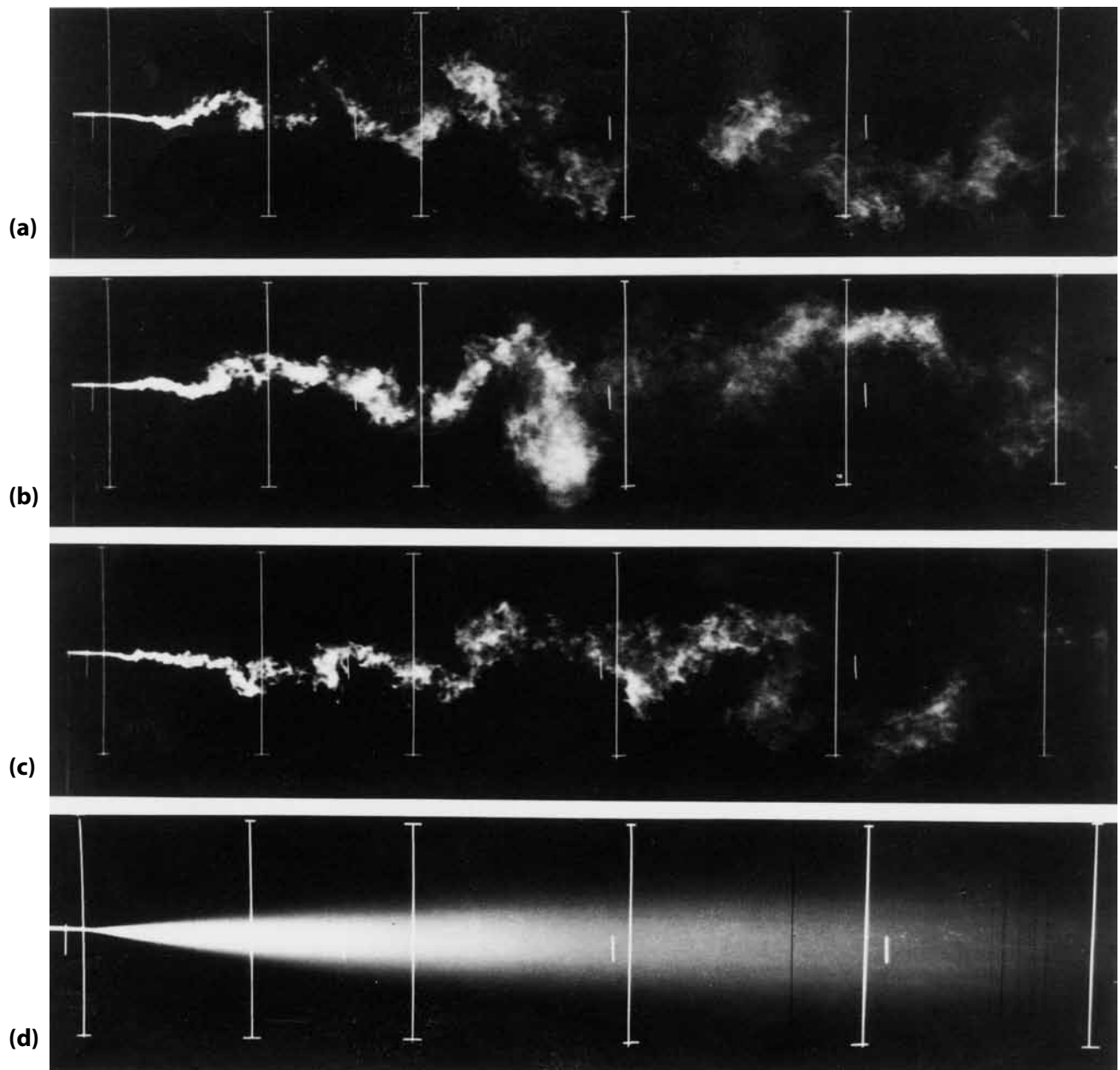


Figure 4.4 Images of smoke plume. Smoke is disseminated on the left and propagates to the right. (a-c) Images are each exposed for 1/60 of a second, capture the smoke plume at different times. (d) The time averaged imaged on the bottom was exposed for four minutes.⁸

the probability that no agent exists in the center of the plume is less than one half of one percent, whereas at the edge of the plume, the probability that no agent exists is nearly a 99 percent.

The mean value of the plume near the edge is dominated by the small chance that turbulent eddies of the type seen in Figure 4.4 a-c will blow a substantial amount of agent there, rather than an indication of there generally being a small

concentration of agent already there. These observations are significant for the deployment of sensors. Because the agent concentration is often zero at the edge of a plume, it is not possible to get high detection probability there, even with a very sensitive sensor. In this particular point release scenario, a high detection probability can only be achieved by having a sufficiently dense array of sensors to ensure that some of these sensors are near the center of the plume.

Footnotes

⁸ Carmen J. Nappo, "Turbulence and Dispersion Parameters Derived From Smoke-Plume Photoanalysis," *Atmospheric Environment*, Volume 18, Number 2, pp 299 – 306, 1984, Pergamon Press Ltd., UK.

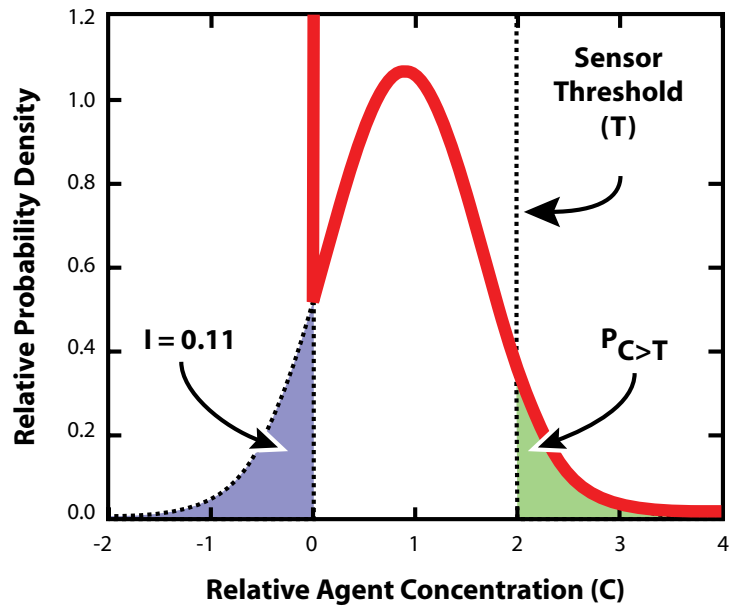


Figure 4.5 The clipped Gaussian relative probability distribution function for the agent concentration, at a particular time and location.

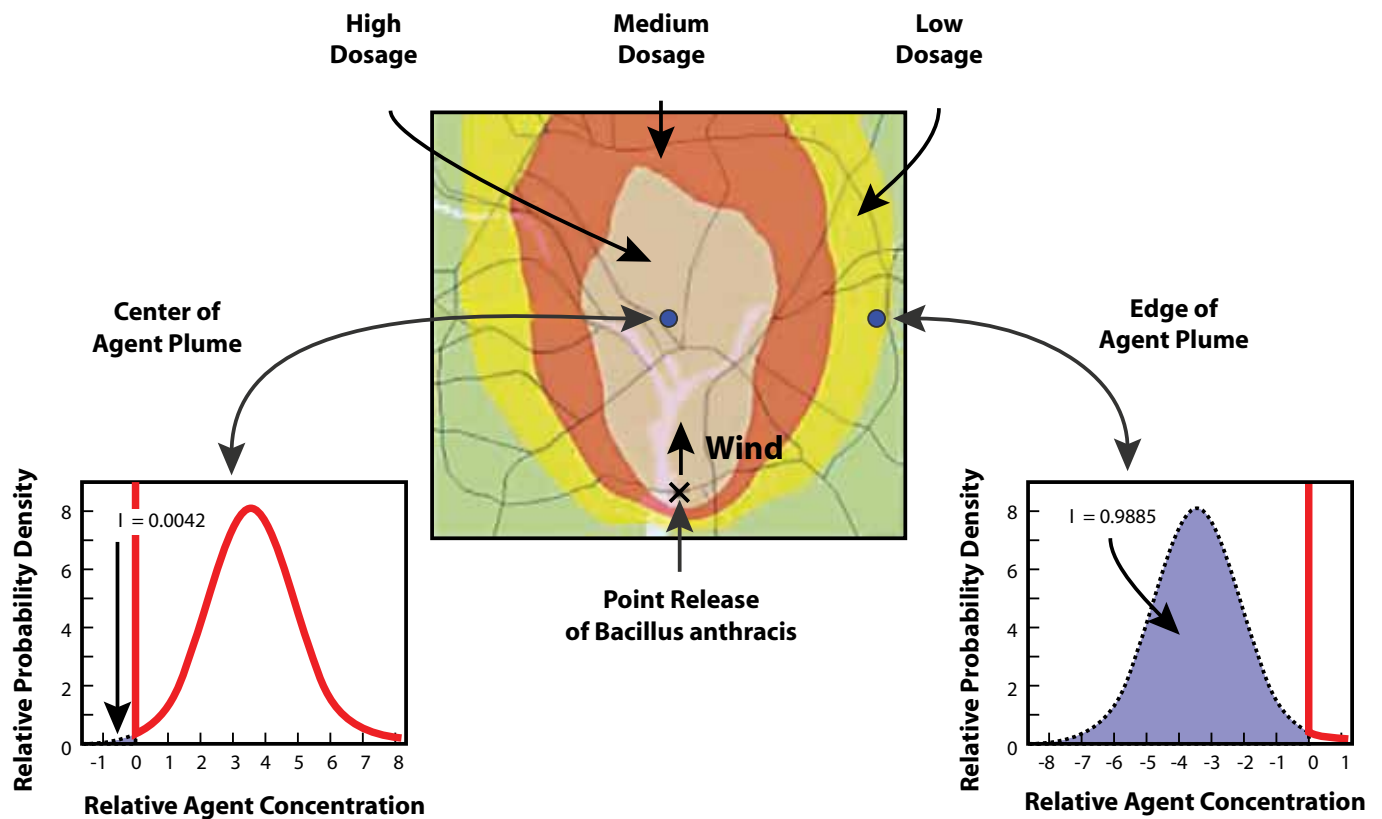


Figure 4.6 The intermittency depends on the location of a sensor within a plume.

Resulting Key Sensor Metrics

Sensitivity and Sensor Density

As indicated above, one of the main benefits of using multirealization analyses is that they generate sensor requirements based on a range of scenario inputs. As a further example of this process, the HPAC simulation code was used to generate the dosage profiles shown in Figure 4.7. The plumes shown in the two figures illustrate the effect of wind speed. A denser portion of the HPAC plume passes over a smaller number of sensors at higher wind speeds, and could easily slip between the sensors. At low wind speeds, more diffuse portions of the plume propagate past more of the sensors.

At low wind speeds, a system of 11 sensors spaced 500 meters apart in the Ground Forces Defense scenario will detect agent release quantities range from 10 grams to 10 kilograms depending on the sensitivity threshold as shown in Figure 4.8. Specifically, a 1ppl sensor will detect a 10 gram release in 2.5 m/s wind, and a 500 ppl sensor will detect a 10 kg release under similar conditions. The contour plots

show the 0.95 confidence level curves for the probability of detection on the release mass versus wind speed graphs. At very low wind speeds the plumes spread by diffusion, and the concentrations are low near the sensors meaning that higher release masses are needed for sensors of a given threshold to detect the plume. At high wind speeds, however, the plume blows right through the widely spaced sensor grid without detection because the intermittency of the plume precludes the array from achieving 95% probability of detection with the assumed sensor spacing.

Figure 4.8 illustrates the detectable release mass as a function of wind speed for two sensor spacing intervals. In these calculations, the agent release is 2-km upwind of the sensor array. The contours represent different concentration thresholds at a detection probability of 0.95. For both the left and right hand graphs, the detectable release mass decreases to a relative minimum and then rises as the wind increases. At low wind speed, the effects of atmospheric dispersion (horizontal and vertical) decreases the agent concentration that the sensors experience. As the wind speed increases from zero, the detectable release mass decreases because the wind more effectively spreads the

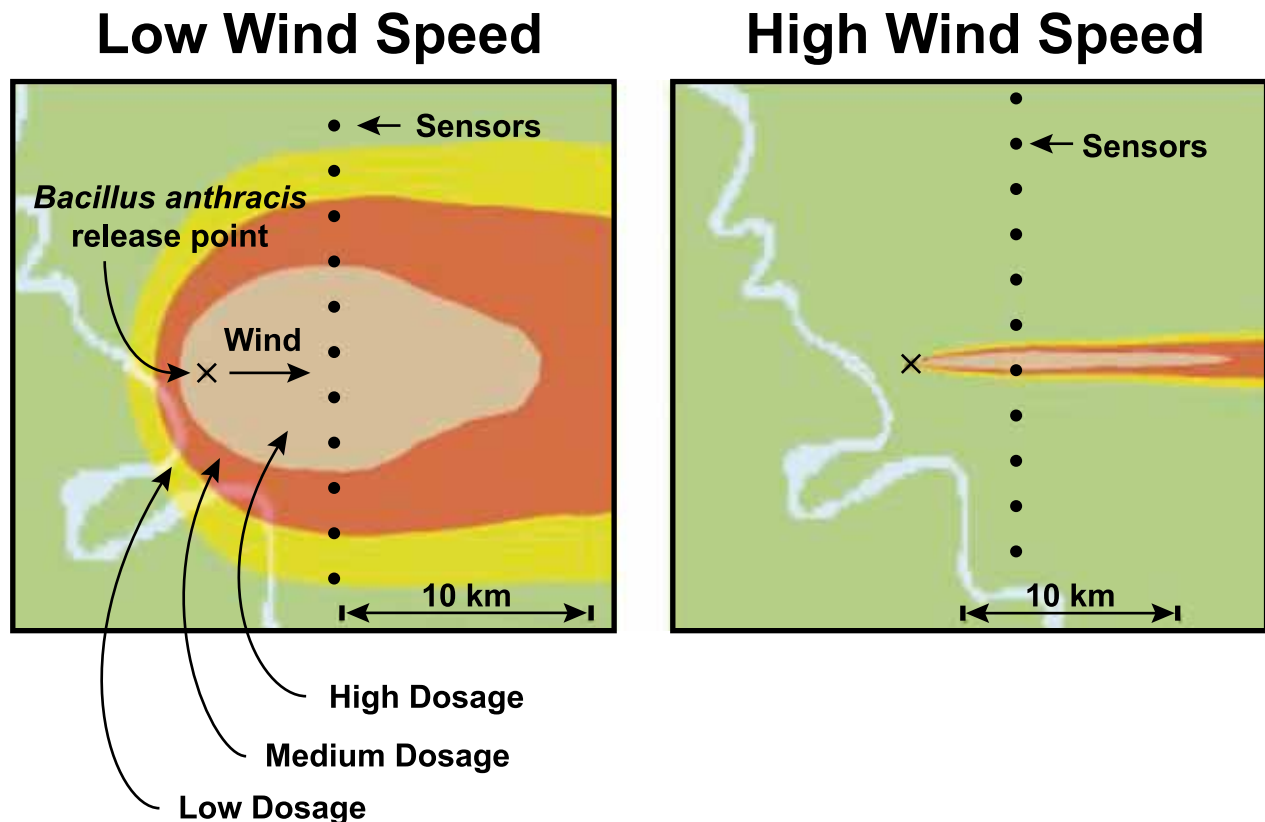


Figure 4.7 Dependence of sensor spacing requirements on windspeed.

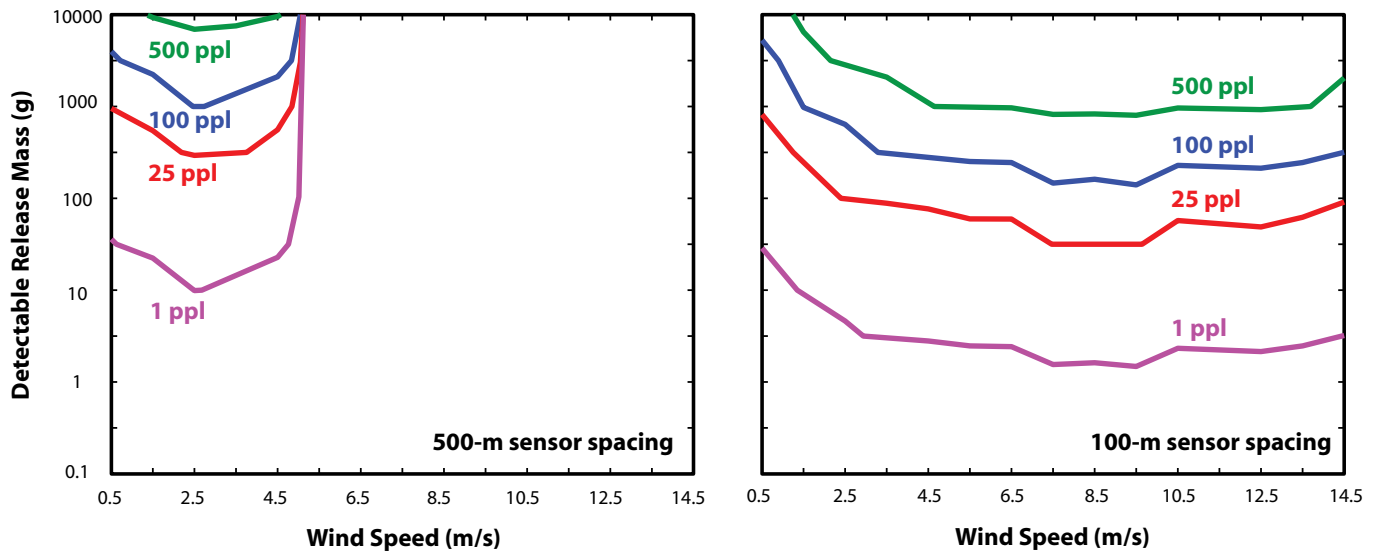


Figure 4.8 Plots of the detectable agent release mass as a function of the wind speed for a linear array of sensors with various concentration sensitivities where agent release is 2-km upwind of the sensor array. Contours represent different concentration thresholds at a detection probability of 0.95.

agent over the sensors. However, at sufficiently high wind speeds the agent is transported downwind at a rate greater than its transverse spread rate and the agent plume can pass between the sensors such that the detectable release mass rapidly increases. Further increases in the wind speed progressively limit the transverse dispersion of the agent cloud in the time that it takes to travel from the release point to the sensors. At sufficiently high wind speeds, the agent plume becomes quite narrow and can pass between the sensors. At this point the release mass required in order for detection to occur rapidly increases. This effect is shown in the left hand plot where the sensors are 500 m apart. At a wind speed of about 5 m/s the detectable concentration rapidly increases. The right hand plot shows that if the sensors are spaced more closely together (100 m) the cloud does not pass between the sensors for the range of wind speeds shown. In this case, a dense array of less sensitive sensors provides more protection than a sparse array of more sensitive sensors.

The dependency of detection on sensor spacing and wind speed on detection is further illustrated in Figure 4.9. Under the same conditions illustrated in Figure 4.8, the 11 sensors spaced 200 meters apart detect the contaminant across all wind speeds. The 100 meter spacing yields positive results down to a release mass of 30 grams across most wind speeds. Further increases in sensor density yield little improvement in performance.

Since the range of release masses and wind speeds in Figures 4.8 and 4.9 are reasonable for the Ground Forces Defense scenario, choosing the sensitivity spider leg to run from 500 to 1 ppl is justified, as is a deployment density between 500 m and 100 m. The release point and geographical location in which the scenario was run were also varied, and these sensitivity and spacing numbers are still reasonable across a spectrum of cases. In this instance, the release distance doesn't dramatically change the needed sensitivity or spacing, however, spacings of 50 m are useful for closer releases.

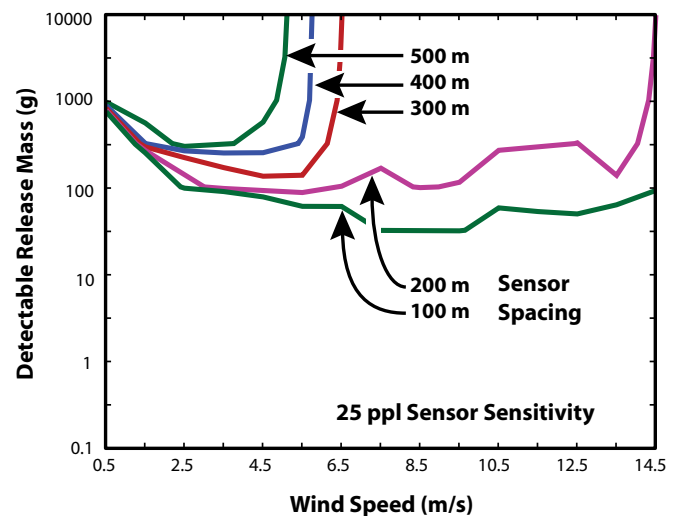


Figure 4.9 Detection contour plots as a function of sensor spacing. The concentration correlation length is 100 m. The array detection probability is 0.95. The release is 2-km upwind of the sensors.

Sensor Response Time

For a detect-to-warn strategy to be effective, the response time (sensor response time plus the protective response time) must be less than or equal to the agent transport time (the time between the agent release and the arrival of the agent at positions to be protected). The protective response time includes notification of the troops in the field, and time for the soldier to enter protective posture (e.g., mask, shelter). Figure 4.10 illustrates the reaction timeline. For the purpose of this study, the protective response time has been taken to be two minutes for all the outdoor scenarios. For the two building scenarios, where the response is an automatic adjustment of the heating, ventilation and air condition (HVAC) system, the response time is 5 seconds.

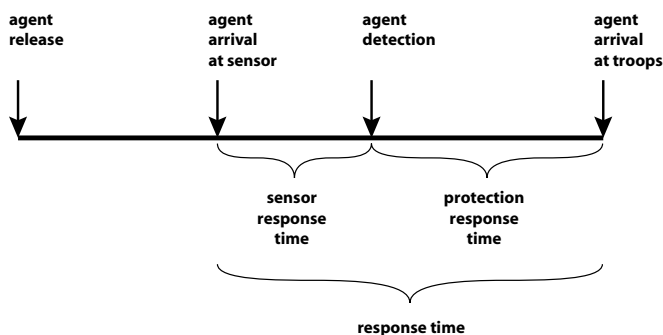


Figure 4.10 Timeline for response to an agent attack.

Figure 4.11 shows the time-dependent detection probability for the Ground Forces Defense scenario at the location of the sensors **in the red curve (referenced to the left axis)** and, the dosage inhaled by a soldier in the agent propagation path some distance downwind **in the blue curve (referenced to the right axis)**. The 11 sensors are

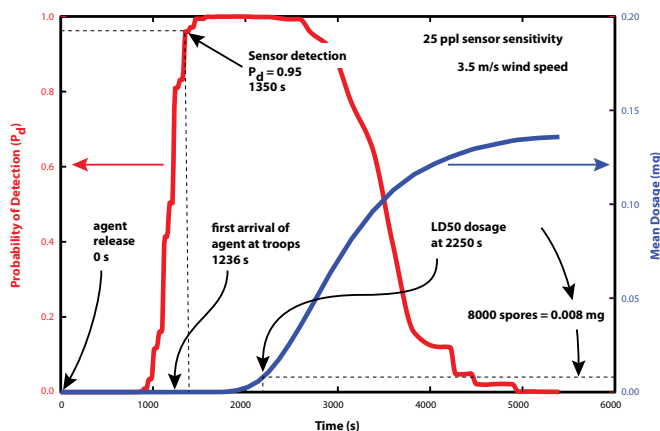


Figure 4.11 Probability of detection and dosage curves showing the limit on reaction time. For this plot, the release occurs 2 km upwind of the sensor array and 4 km upwind of the troops.

spaced 100 meters apart on a transverse line two kilometers from the release point. The mean wind is 3.5 meters per second. The array of detectors is slightly off of the center line of the plume and the correlation scale length is 100 meters.

Under these conditions, the sensor array **does not achieve a 95 percent probability of detecting** the agent until after the first arrival of **small quantities** of agent at the troops. The time between agent detection and the troop acquisition of an LD50 dose (8000 spores) is 15 minutes. Figure 4.12 shows how this LD50 time is dependent on the wind speed.

Figure 4.12 shows an example of the response times as a function of the range of wind speeds characteristic of an important Middle East location. The total response time (see Figure 4.9) is the time from when the agent arrives at the sensors, with a 95 percent probability of the concentration exceeding the sensor detection threshold, until the troops receive an LD50 dose.

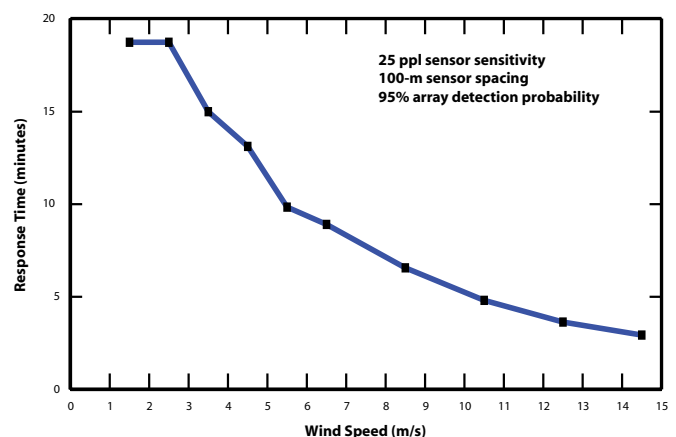


Figure 4.12 The total response time as a function of wind speed. The transport time is taken as the time between the agent release and the time that the troops receive an LD50 dosage.

At high wind speeds, the response time in the Ground Forces Defense scenario is under three minutes. Since the time it takes for alarms to be relayed to the appropriate units and the soldiers to don their masks can be as long as two minutes, a sensor must communicate a detection shortly after the agent concentration reaches its detection threshold—within 1 minute—to be fully useful in the scenario. However, a sensor that takes as long as five minutes would still provide protection in wind speeds of 6 m/s or less, which are quite common in this scenario. When this result is combined with those for other release points, the response time leg of the spider chart can be chosen to run from about 15 minutes to one minute. At the inner

boundary, the sensor will help protect troops in low wind conditions only, while a sensor that triggers within one minute will give the troops time to don gear in almost all cases.

False Positive Rate

An attempt was made to bound the acceptable false positive rate for each scenario by comparing the risks and costs associated with using versus not using agent sensors. The principal risk of the latter is casualties resulting from an undetected attack. The costs and risks of using sensors include both the cost of the sensors and the consequences of responding to false positives. The analysis of false positives required an understanding of how the troops will respond to a false positive, and how well they perform in MOPP⁹ gear. This response information was available only for the movement-to-contact and deliberate defense scenarios (Section 5.0, Scenarios 2 and 11). Even for those scenarios, the response data are out of date because testing was performed using outmoded gear. Tolerable false positive rates for the other scenarios are estimated using the judgment of the panel. A more detailed discussion of the false positive rate analysis is given in Appendix II.

Findings

When considering sensor sensitivity and sensor spacing, the scenarios can be divided into two primary release categories: Moving point releases (or line releases) and Stationary point releases.

For scenarios with moving point releases, the detectable agent concentration tends to be insensitive to sensor spacing because the attacker spreads the plume over a large area. However, these scenarios demand very sensitive detectors. In contrast, for scenarios with stationary point releases, a dense array of sensors is required in order to ensure an acceptable detection probability of agent releases. Although, stationary point release scenarios do not need sensors with as much sensitivity.

When considering sensor response time, the scenarios can be divided into two different categories: detect-to-warn and detect-to-treat.

Footnotes

⁹ Mission Oriented Protective Posture



5.0 SCENARIOS

The premise of the investigation for the Chemical and Biological Sensor Standards Study (CBS3) is that the requirements for the sensors are dependent upon their operational context. The sensor development community should use these operational requirements to define the specifications for their design objectives. The sensor requirements were determined in the analysis for Phase II of CBS3 by calculating the values of the system parameters needed to detect a variety of attacks. A diverse set of

scenarios was needed to describe typical operational contexts for chemical and biological (CB) defense systems. The diversity of the scenarios will help key decision makers understand the trade-offs among sensor system parameters in terms of operational effectiveness specifically with regard to sensitivity, probability of detection, false positive rate, sensor response time, location and spacing of the sensors, and the acquisition and maintenance costs.

Scenario		Agent	Release Type	Release Comments
1	Convoy Movement	Anthrax	Single Point	Stationary sprayer
2	Convoy Movement	Sarin	Single Point	Stationary sprayer
3	Ground Forces Defense	Anthrax	Single Point	Stationary sprayer
4	Military Building (internal attack)	Smallpox	Single Point	Slow release from box
5	Military Building (external attack)	TIC	Single Point	Tanker truck explosion
6	Amphibious Operation	Mustard	Multiple Point	Mines
7	OCONUS Forward Airbase	VX	Multiple Point	Missile air bursts
8	Terrain Denial	VX	Multiple Point	Artillery air bursts
9	CONUS Military Post	Anthrax	Multiple Point	Backpack sprayers
10	CONUS Military Post	Anthrax	Line	Aircraft sprayer
11	Defensive Positions	Sarin	Line	Moving truck with sprayer
12	Defensive Positions	Anthrax	Line	Aircraft sprayer
13	Naval Port Facility	Anthrax	Line	Moving truck with sprayer
14	Navy Ship in Littoral	Plague	Line	Small boat with sprayer

OCONUS – Outside Continental United States

CONUS – Continental United States

TIC – Toxic Industrial Chemical

VX and Sarin – Common names for two toxic chemicals

Table 5.1 Scenarios developed to generate CB sensor requirements.

For Phase II of the CBS3 project, the scope and validity of the determination of sensor requirements was expanded to the fourteen multirealization CB defense scenarios shown in Table 5.1. In contrast to the single realization scenario employed in Phase I of the study, a multirealization scenario utilizes a range of agent release characteristics including release mass, wind speed, geographic location, etc. The result is a more comprehensive description of sensor requirements than could be achieved with a single realization analysis.

To construct the scenarios, the Panel assembled a matrix of relevant scenario characteristics including:

- Targets (e.g., Advancing Troops, Airbase, Port, Office Building, etc.)
- Release Types (e.g., Point, Line, Multiple points)
- Agents (e.g., Anthrax, Sarin, Smallpox, etc.)
- Response Goals (e.g., avoid exposure, etc.) and Methods (e.g., personal protection, HVAC modification, etc.)

From this matrix, a set of scenario characteristics was chosen to construct the 14 scenarios presented in this section. It should be noted that the objective of the panel was not to develop an exhaustive list of possible mission scenarios but rather a practical number of variations that provides a relatively comprehensive view of the important threat space relevant to each branch of the United States military.

The Panel also specified that the goal of the investigation was detect-to-warn protection strategies with point sensors for aerosol and vapor threats. The results for the 14 scenarios in Table 5.1 are described in this chapter of the report.

The list of scenarios was developed to provide a sample of military contexts and possible wartime situations in which detect-to-warn sensors might be deployed. As such, the results are not meant to be restricted to the combat situations in the specific geographic areas or to prescribe tactics, techniques, or procedures to handle these situations. Rather, the investigation should yield solutions that can be interpreted for applications in military missions in general. The section on each scenario includes a brief description of the tactical situation that covers the disposition and activities of the opposing and the friendly forces and the environmental factors that might influence the effectiveness of the attack or the sensors themselves. Paragraphs on the Scenario Summary and the Scenario Results, two tables of data, and the corresponding spider chart are constructed from the multirealization analyses. The definitions of the scenario specifications are listed in Table 5.2. For all outdoor scenarios the wind speeds we taken to range from 1 – 15 m/s.

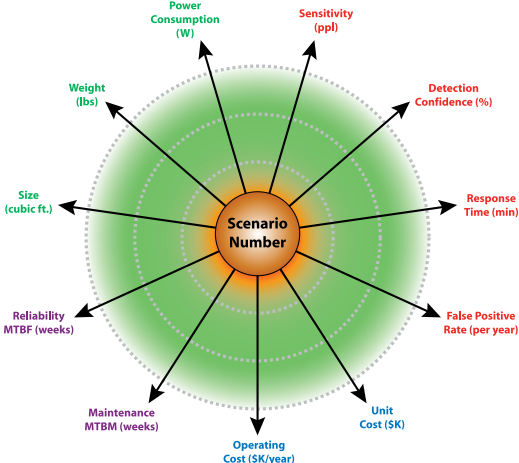
Scenario Details		Spider Chart
Agent of Operation	General description of attack location	
Personnel Involved	Military units involved in attack	
Sensor Positions	Position of sensors with respect to area of operation	
Sensor to Protected Area Distance	Distance from sensors to troops or area that is being protected	
Sensor Mission Duration	Total active time of sensors	
Protective Response Time	Time required for troops to enter protective posture	
Attack Parameters		
Agent	Biological or chemical agent used in scenario	
Release Type	Description of release type (point, multi-point, or line) and release mechanism	
Release Mass	Total mass of agent released in scenario	
Release Distance From Sensors	Upwind distance from agent release to sensors	
Multi-realization Scenario Analysis		
Sensor Sensitivity	Sensitivity required to achieve protection	
Sensor Spacing	Spacing between sensors in a sensor array. The spacing is chosen to achieve high probability of agent exposure for at least one sensor	
Sensor Response Time	Time from sensor exposure to agent and sensor alarm	

Table 5.2 Definitions of scenario specifications and example spider chart.

Synopsis of the Scenarios

The approach to the CBS3 investigation was to find the specifications that would be required for point sensors to be effective in fourteen multirealization scenarios. The standard for effectiveness was defined to be detect-to-warn, the most challenging objective for a level of protection. The results are stated in terms of ranges of values for sensor sensitivity, spacing, response time, and false-positive rates. See the values for the first three parameters in the table Multirealization Scenario Analysis for each scenario. There are axes on the corresponding spider chart for the false-alarm rate in addition to the three axes for sensitivity, spacing, and response time.

For the purposes of our analysis, we have assumed that, in each of the scenarios, a nuclear, biological, and chemical (NBC) defense plan for the deployment of point sensors has been defined and that it was implemented by the personnel involved. In all cases, the results show that it is possible to determine specifications for point sensors that will help with the detect-to-warn objective at least to some degree. However, for a number of the scenarios, point sensors cannot constitute the complete solution.

It is important to make clear that the results of the CBS3 investigation are not influenced by the state of the art of sensor technology. Indeed, we are fully aware that, by current standards, some of the results include specifications for extremely sensitive detectors or sensors with extremely low false alarm rates. In such cases, we are simply reporting results from the analysis of the scenario. For example scenario 9 involves the internal attack on a large military base. To achieve fast and high probability detection of this event requires a very large number of sensors and in order to achieve a low false alarm rate for the overall military base the sensor false alarm rate must be exceeding low. In all scenarios, the sensors are assumed to act independently of one another. There may be methods to utilize sensors with substantially higher false alarm rates by processing the outputs of multiple sensors together with auxiliary sensors, in a more sophisticated way for declaring a general alarm. Such methods (of which there are many) were not considered as part of this study.

While we have not taken up a discussion of the details in this report, it is clear from our results that intelligence, stand-off sensors, and other means will be required, in addition to the point sensors, for practical and reliable detect-to-warn protection against the attacks in several of the scenarios.

Scenario Summary

Lightweight, hand-portable sensors have been deployed on both sides of a 20-mile long corridor for a main supply route (MSR). The detectors are disposable, ruggedized, and battery powered. They are capable of wireless communication. In order to conserve the sensor's battery energy consumption, each upwind sensor is activated (via wireless communications) only for times encompassing the passage of convoys. It is anticipated that as many as 10 convoys per day, each of one hour duration, pass the sensors over the MSR duration of one week.

Enemy forces employ a stationary sprayer filled with *Bacillus anthracis* (anthrax) at a location upwind from the array of sensors. The agent is released under meteorological conditions favorable for agent propagation toward the MSR and for interception of a convoy. The sensors detect the anthrax cloud and transmit warnings that signal the convoy to take protective measures.

Scenario Details

Defense Posture

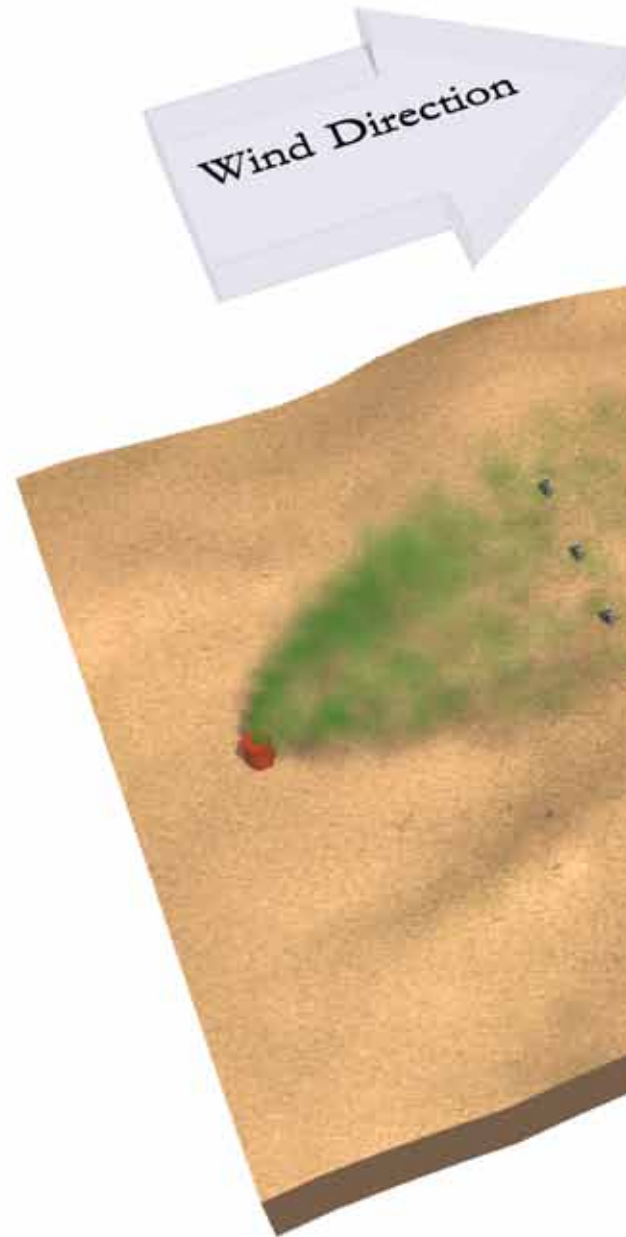
<i>Agent of Operation</i>	Main supply route (MSR)
<i>Personnel Involved</i>	Military combat brigade
<i>Sensor Positions</i>	Along both sides of 20-mile road
<i>Sensor To Protected Area Distance</i>	1.5 - 4 km
<i>Sensor Mission Duration</i>	1 hour x 10 convoys x 7 days = 70 hours
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	<i>Bacillus anthracis</i> (anthrax)
<i>Release Type</i>	Single point release from ground level stationary sprayer
<i>Release Mass</i>	0.01 - 1 kg
<i>Release Distance From Sensors</i>	0.5 - 8 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	1 – 500 ppl
<i>Sensor Spacing</i>	50 – 500 meters
<i>Sensor Response Time</i>	1 – 10 min

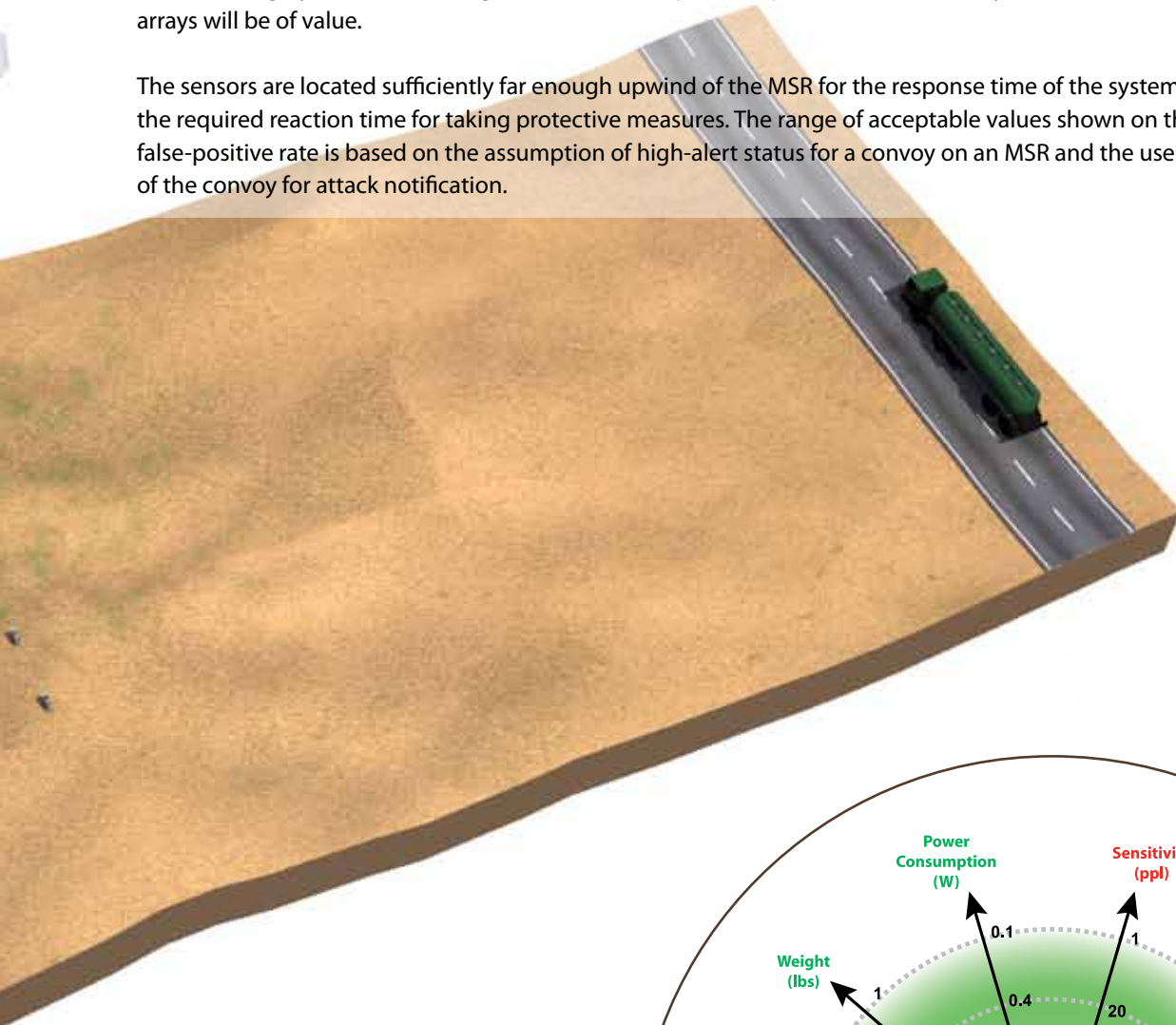


5.1 Convoy Movement (Biological/Single Point Release)

Scenario Analysis

Depending on wind speed and turbulence, the expected distribution of the aerosol in this scenario will vary from widely spread concentrated puffs to a steady narrow stream. The calculations show that there will be significant concentrations at ground level across the spectrum of weather conditions. For such a single point, sustained release, the detectors need not be highly sensitive. However, the array must be closely spaced to be sure that one or more of the point sensors will be positioned within the highly concentrated region of the narrow plume expected in a stiff, steady breeze. In calmer air, widely spaced arrays will be of value.

The sensors are located sufficiently far enough upwind of the MSR for the response time of the system to be greater than the required reaction time for taking protective measures. The range of acceptable values shown on the spider chart for the false-positive rate is based on the assumption of high-alert status for a convoy on an MSR and the use of only sensors upwind of the convoy for attack notification.



Scenario Summary

Lightweight, air-dropped sensors have been deployed on both sides of a 20-mile long corridor for an avenue-of-advance (AA). The detectors are disposable, ruggedized, and battery powered. They are capable of wireless communication. In order to conserve the sensor's battery energy consumption, each sensor is activated (via wireless communications) only for times encompassing the passage of the convoy. It is anticipated that the convoy movement has a one hour duration.

Enemy forces open the valve on a stationary sprayer filled with Sarin gas upwind from the array of sensors and the AA. The agent is released under meteorological conditions favorable for a chemical weapon. The attack is timed for the interception of the convoy. The sensors detect the Sarin in the air and transmit a signal for the convoy to take protective measures.

Scenario Details

Defense Posture

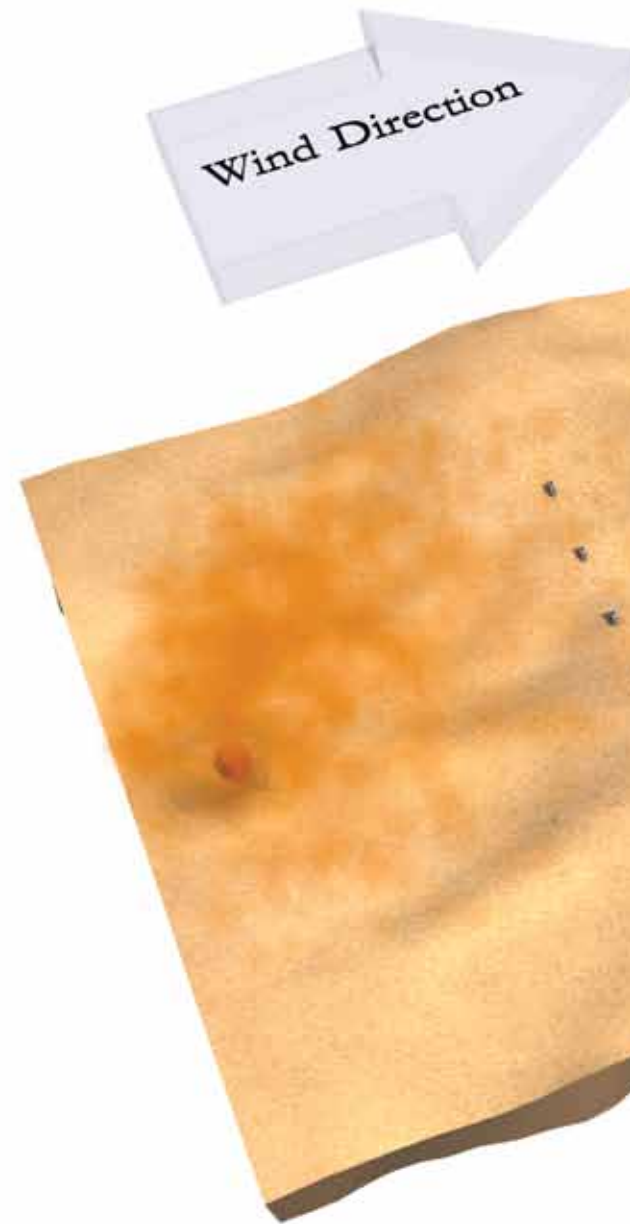
<i>Agent of Operation</i>	Avenue of advance
<i>Personnel Involved</i>	Military combat brigade
<i>Sensor Positions</i>	Along both sides of 20-mile road
<i>Sensor To Protected Area Distance</i>	1.5 - 4 km
<i>Sensor Mission Duration</i>	1 hour
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	Sarin gas
<i>Release Type</i>	Single point release from ground level stationary sprayer
<i>Release Mass</i>	225 - 450 kg
<i>Release Distance From Sensors</i>	0.5 - 8 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.1 – 10 mg/m ³
<i>Sensor Spacing</i>	50 – 100 meters
<i>Sensor Response Time</i>	1 – 10 min

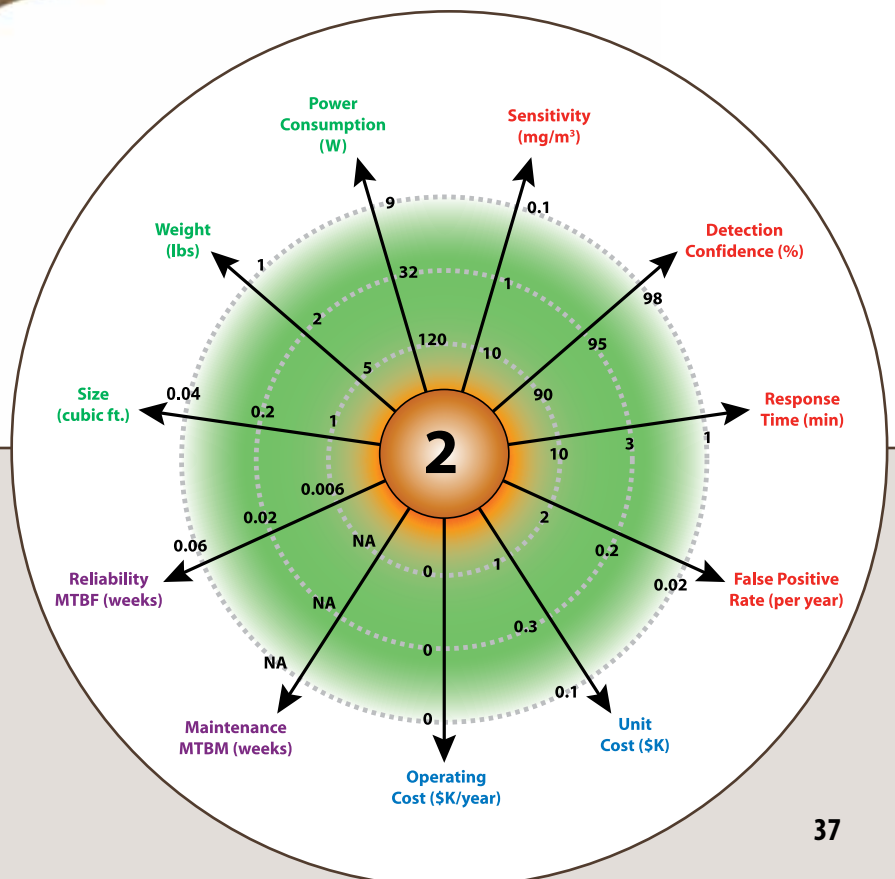
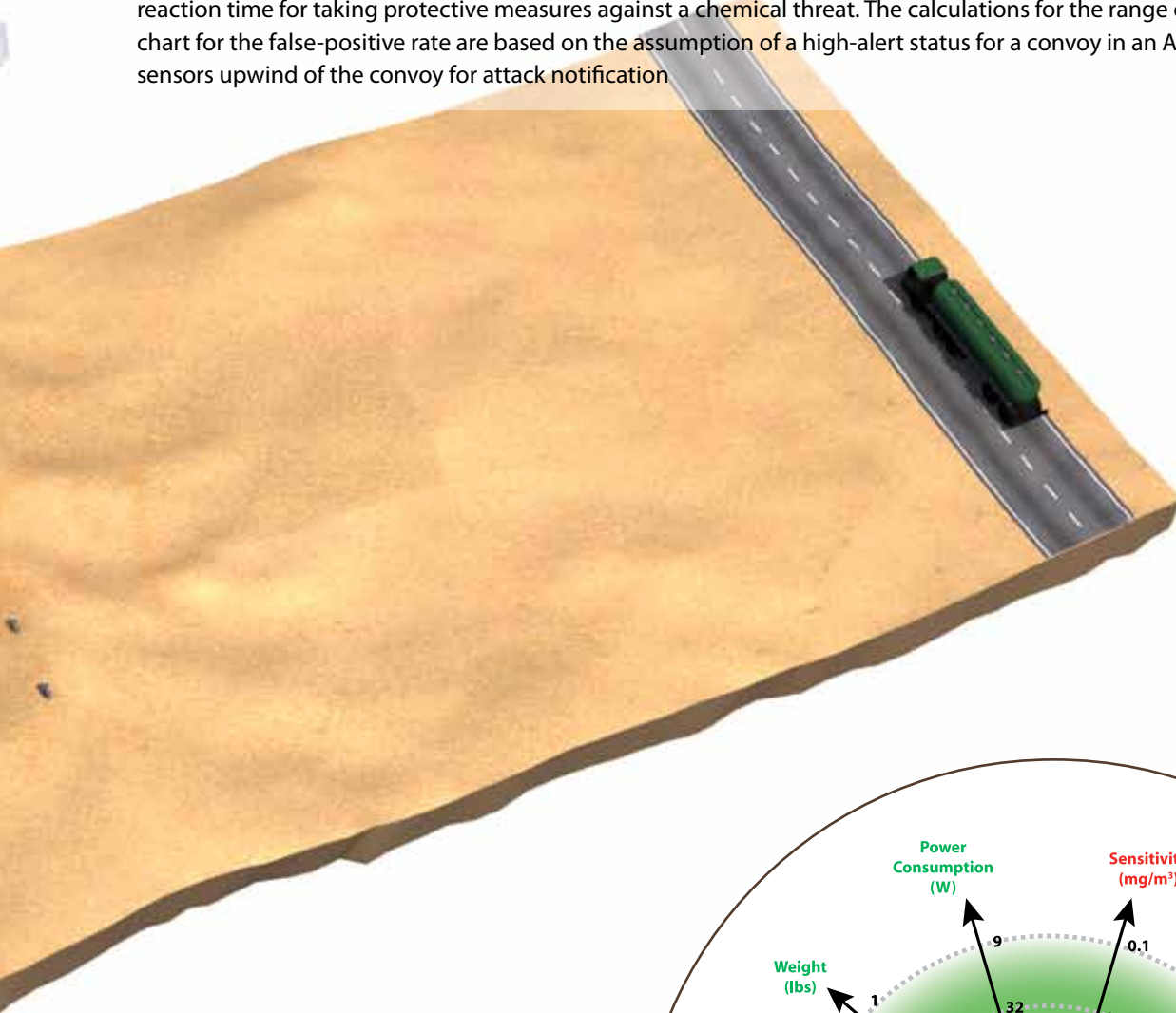


5.2 Convoy Movement (Chemical/Single Point Release)

Scenario Results

For the single point, sustained release, the detectors need not be highly sensitive. However, the array must be closely spaced to be sure of multiple locations of the sensors within the narrow plume expected in a brisk, steady breeze. Under milder weather conditions, widely spaced arrays will be of value.

The sensors are positioned far enough upwind of the AA for the response time of the system to be greater than the required reaction time for taking protective measures against a chemical threat. The calculations for the range of values on the spider chart for the false-positive rate are based on the assumption of a high-alert status for a convoy in an AA and the use of only sensors upwind of the convoy for attack notification



Scenario Summary

Friendly combat forces have taken a defensive position for their part in a planned campaign. They have deployed a line of biological agent sensors upwind of their position. At the end of the campaign these sensors will be retrieved.

The enemy uses a stationary sprayer filled with *Bacillus anthracis* (anthrax) at a location upwind from the array of sensors and the defensive position. The timing of the release is coordinated with meteorological conditions favorable for a biological weapon. The sensors detect the agent and sound the alarm. The personnel in the propagation path of the attack are warned to take protective measures.

Scenario Details

Defense Posture

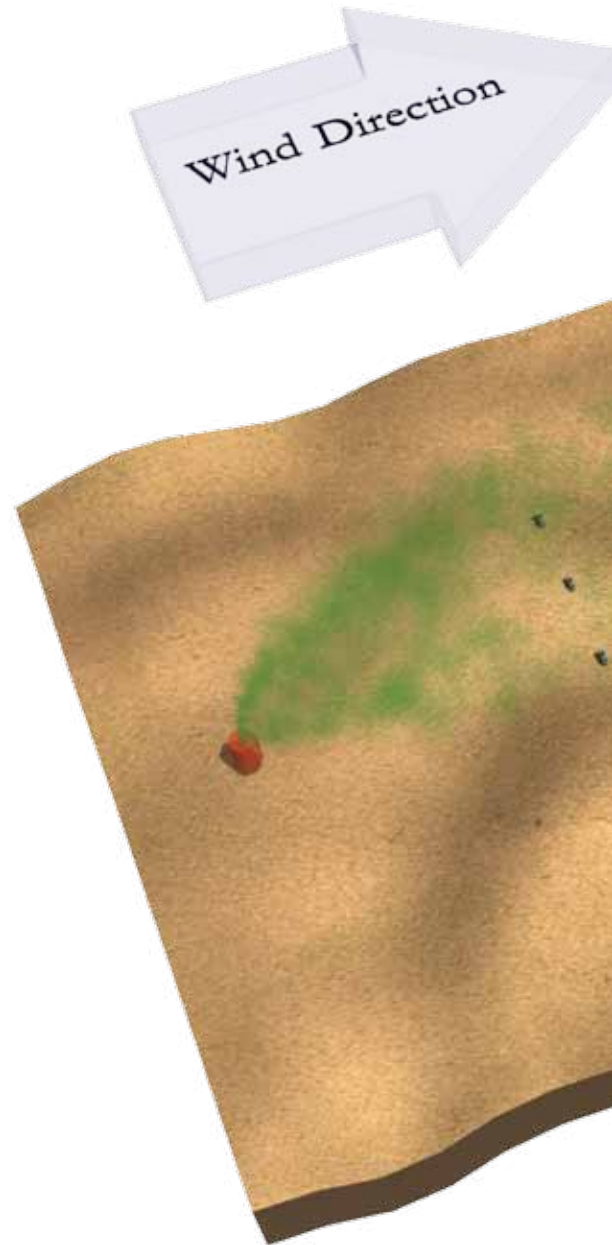
<i>Agent of Operation</i>	US combat forces defensive position
<i>Personnel Involved</i>	2 – 3 battalions
<i>Sensor Positions</i>	Between enemy and US forces
<i>Sensor To Protected Area Distance</i>	1.5 - 4 km
<i>Sensor Mission Duration</i>	24 hours
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	<i>Bacillus anthracis</i> (anthrax)
<i>Release Type</i>	Single point release from ground level stationary sprayer
<i>Release Mass</i>	20 g – 1 kg
<i>Release Distance From Sensors</i>	0.5 - 8 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	1 – 500 ppl
<i>Sensor Spacing</i>	50 – 100 meters
<i>Sensor Response Time</i>	1 – 10 min

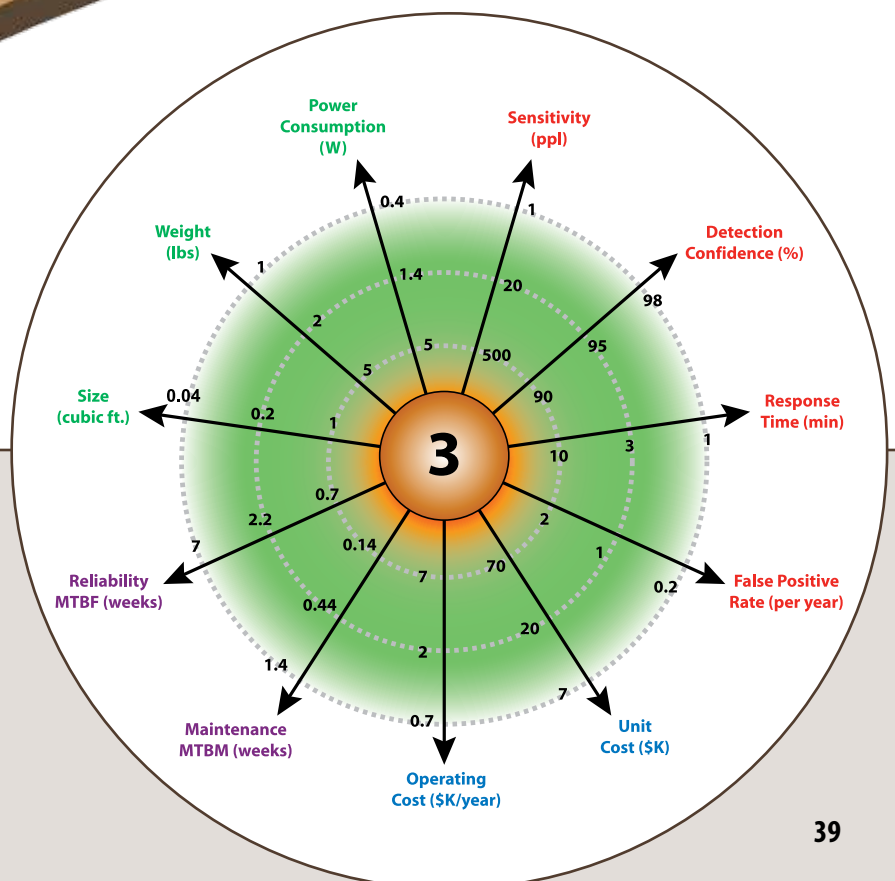
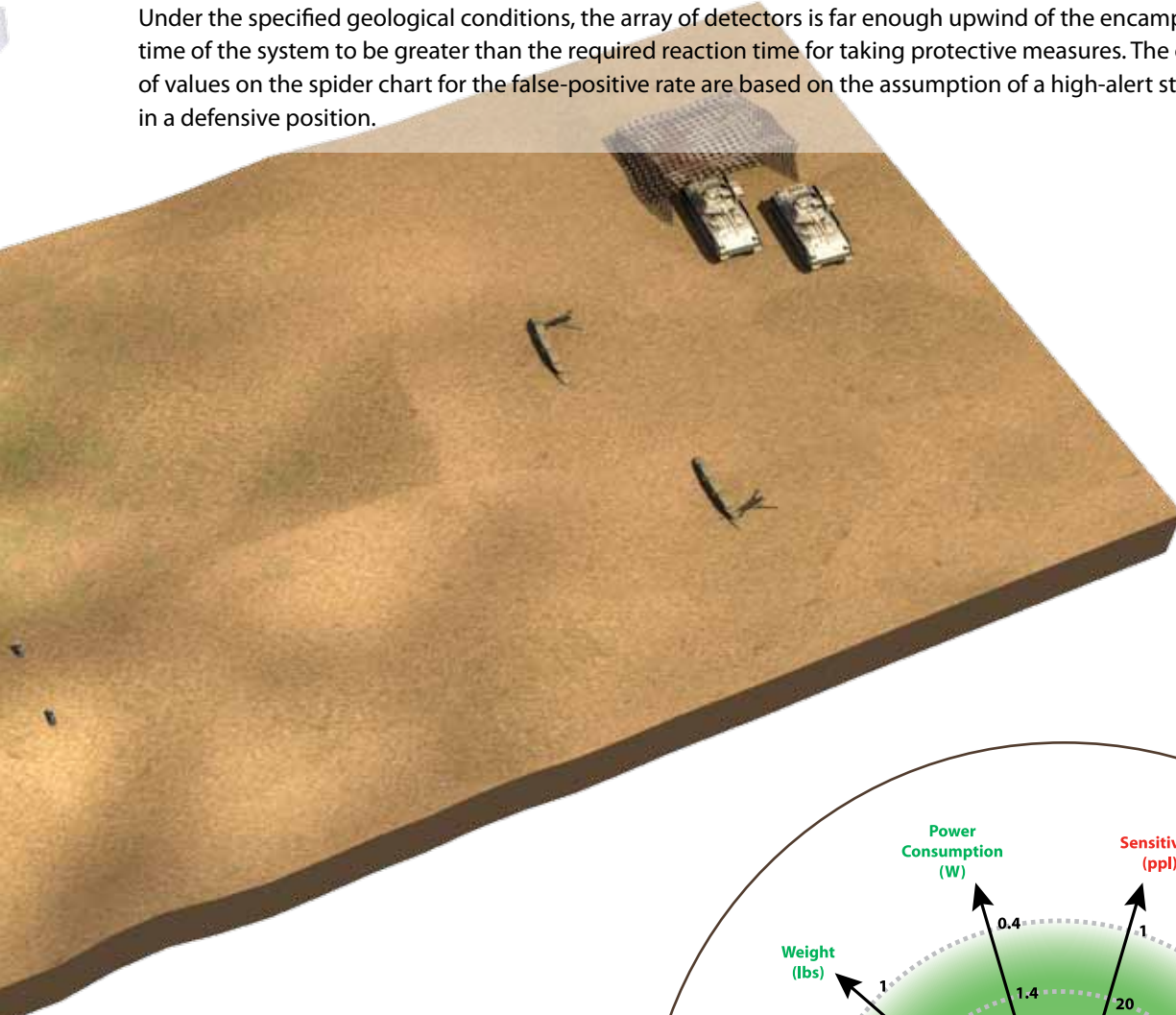


5.3 Ground Forces Defense (Biological/Single Point Release)

Scenario Results

Depending on wind speed and turbulence, the expected distribution pattern of the release of the agent will vary from widely spread dense puffs to a steady narrow stream. Across the spectrum of weather conditions, the calculations show that significant concentrations will propagate at ground level. For the single point sustained release, the detectors need not be highly sensitive. However, the array does have to be closely spaced to be certain of sensor locations within the narrow plume expected in a stiff, steady breeze. In calmer weather conditions, widely spaced sensors would still be of value.

Under the specified geological conditions, the array of detectors is far enough upwind of the encampment for the response time of the system to be greater than the required reaction time for taking protective measures. The calculations for the range of values on the spider chart for the false-positive rate are based on the assumption of a high-alert status for troops deployed in a defensive position.



Scenario Summary

A terrorist joins the janitorial staff at the operations center for an Air Force base. While working on the job, he places a device designed to release a small amount of aerosolized Variola major (smallpox) into the facility's air-handling system. According to the requirements for a detect-to-warn defense on the base, sensors for biological agents have been installed in the air-return ducts throughout the building. A sensor detects the smallpox and transmits a signal to the HVAC system for redirection of airflow in the building. The area of contamination is contained and airflow patterns are rebalanced.

Scenario Details

Defense Posture

<i>Agent of Operation</i>	Embarkation facility for deployment overseas
<i>Personnel Involved</i>	1,000 people
<i>Sensor Positions</i>	In building air return ducts
<i>Sensor To Protected Area Distance</i>	Near zero
<i>Sensor Mission Duration</i>	One month per year
<i>Protective Response Time</i>	1.5 min

Attack Parameters

<i>Agent</i>	Variola major (smallpox)
<i>Release Type</i>	Single point release
<i>Release Distance From Sensors</i>	Near zero

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.1 – 100 ppl
<i>Sensor Spacing</i>	One in every return air duct
<i>Sensor Response Time</i>	0.1 – 1 min

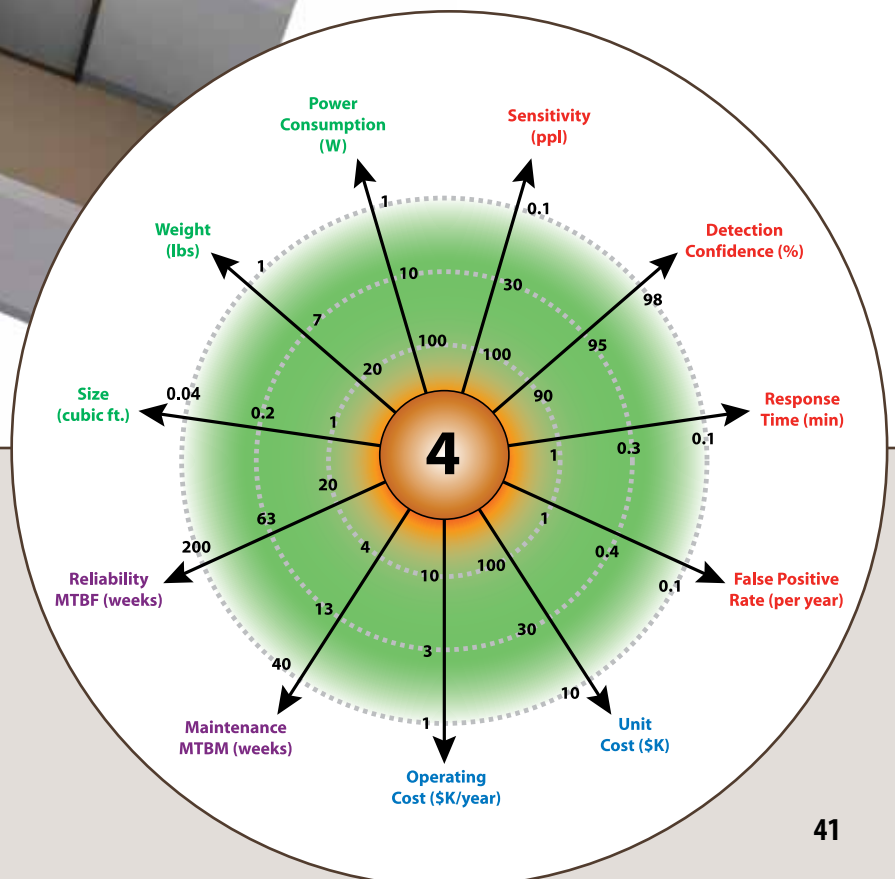
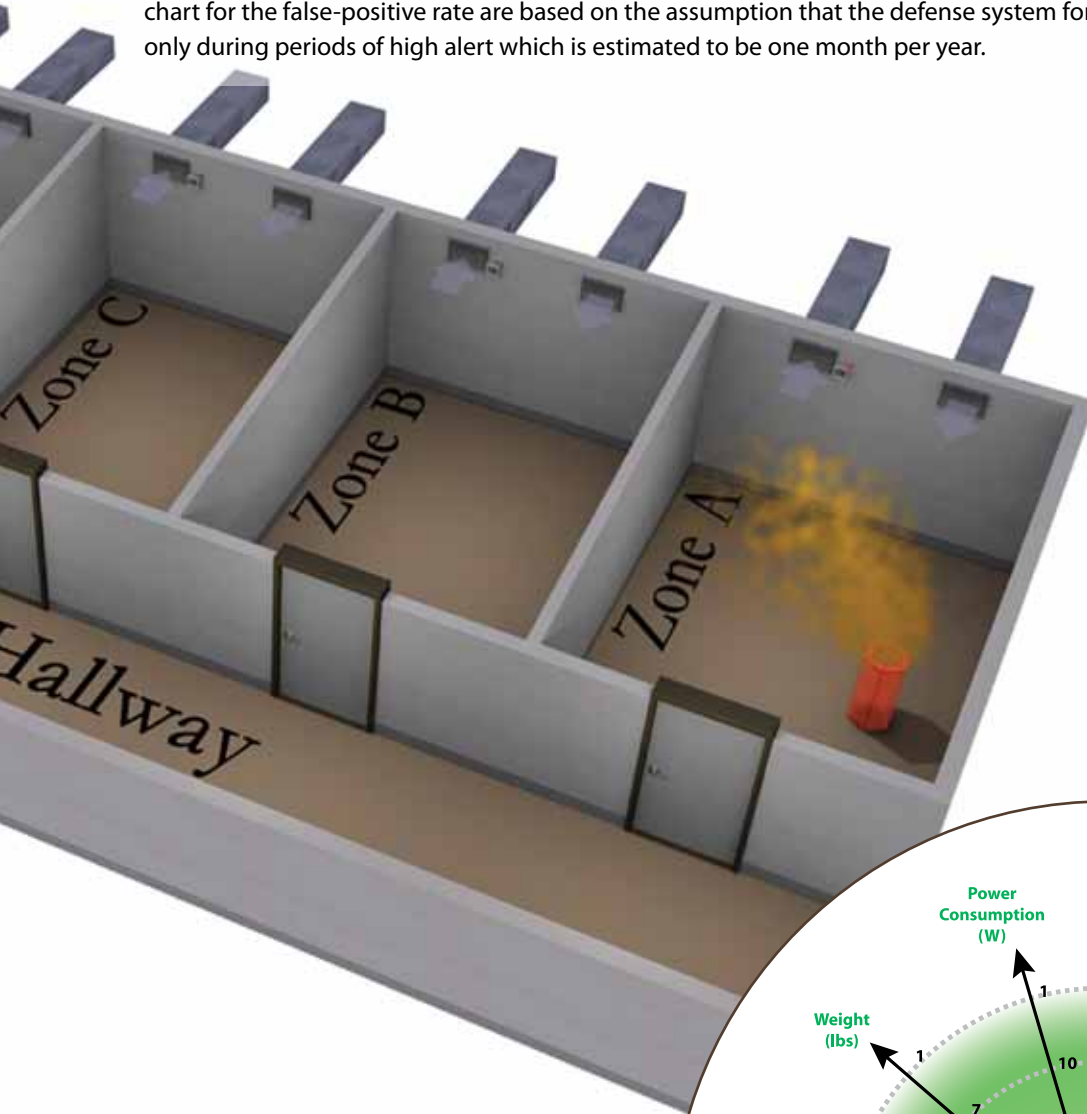


5.4 Internal Attack on a Military Building (Biological/Single Point Release)

Scenario Results

Moderately high sensitivity may be required for the detection of the small amount of smallpox virus that is gradually released in a single zone of the building. A fast response time for the sensors is needed to stop the HVAC system from transporting the agent into the other occupied areas.

Cost is a factor because sensors are needed in every air-return duct. The calculations for the range of values on the spider chart for the false-positive rate are based on the assumption that the defense system for a military building must be active only during periods of high alert which is estimated to be one month per year.



Scenario Summary

A group of terrorists explodes a tanker upwind from a sensitive military building. The tanker contains methyl isocyanate - a toxic industrial chemical (TIC). The vapor from the explosion propagates over the building. A sensor designed for several types of TIC's is installed on the roof inside the fresh-air intake vent. The device detects the chemical and transmits a signal to the building's air handling system. The intake is shut down and contaminated air is no longer actively drawn into the building. People are restricted from leaving building during the period of alert.

Scenario Details

Defense Posture

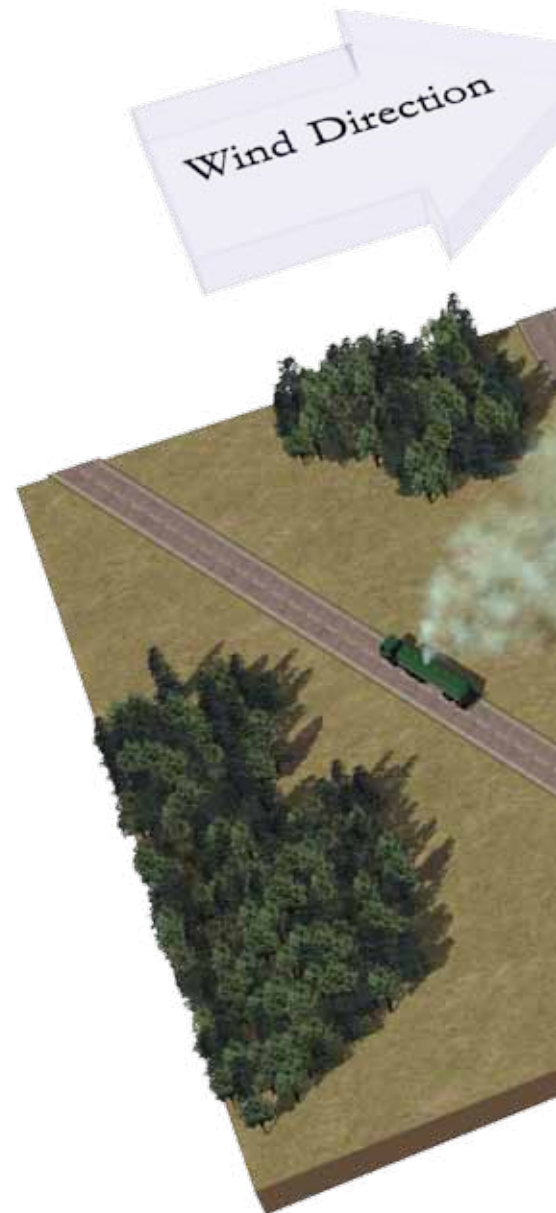
<i>Agent of Operation</i>	Embarkation facility for deployment overseas
<i>Personnel Involved</i>	1,000 people
<i>Sensor Positions</i>	In air intake on building roof
<i>Sensor To Protected Area Distance</i>	Near zero
<i>Sensor Mission Duration</i>	4 hours per activation
<i>Protective Response Time</i>	10 s

Attack Parameters

<i>Agent</i>	TIC (methyl isocyanate)
<i>Release Type</i>	Single point release from tanker truck explosion
<i>Release Distance From Sensors</i>	0.5 – 5 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.5 – 500 mg/m ³
<i>Sensor Spacing</i>	One in roof top HVAC intake
<i>Sensor Response Time</i>	0.1 – 1 min

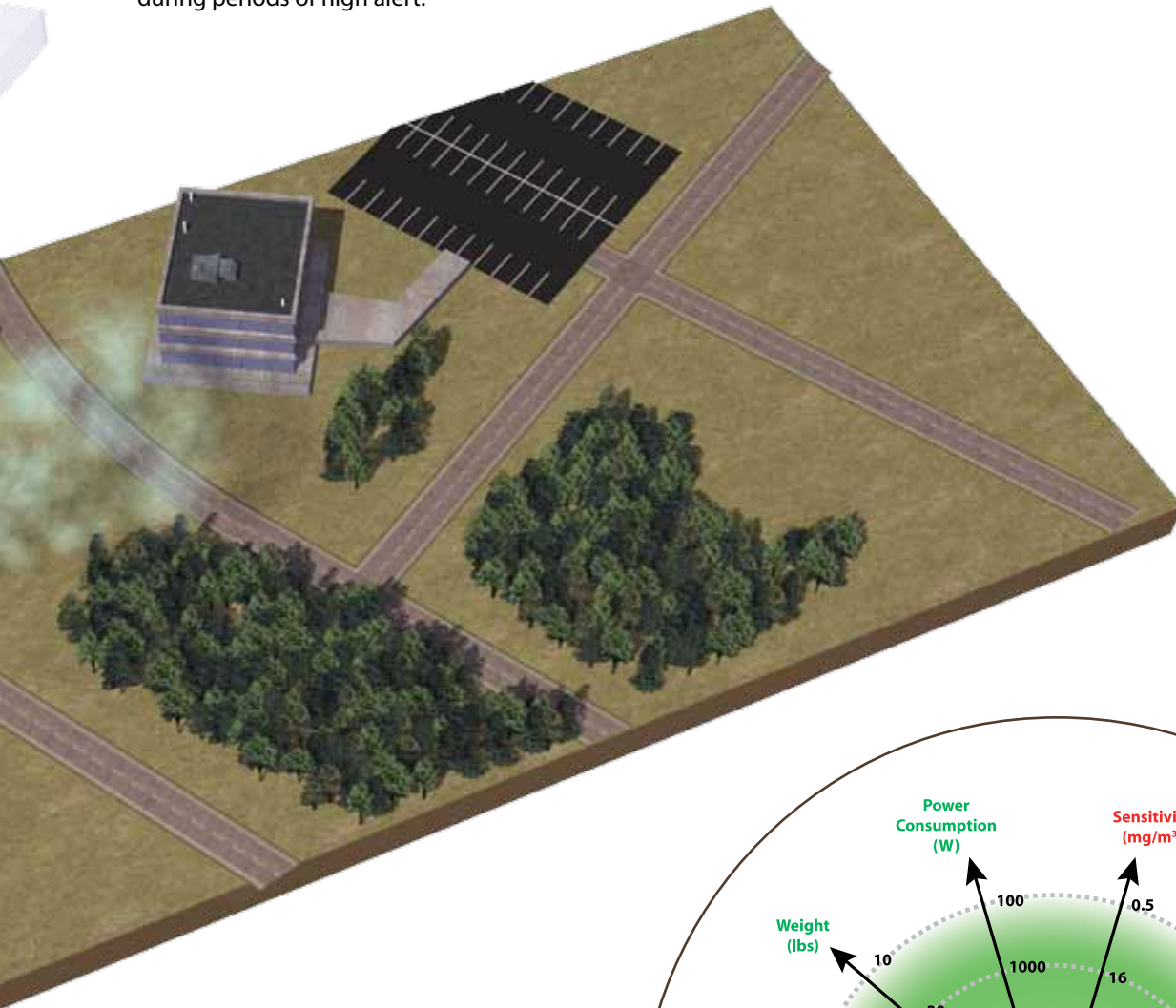


5.5 External Attack on a Military Building (Chemical/Single Point Release)

Scenario Results

The range of values for sensitivity on the spider chart reflects the fact that the large quantity of agent released from the exploding tanker is not difficult to detect. However, the response time is critical because a fast sensor is needed to stop the HVAC system from transporting the agent into the vulnerable regions of the building.

Cost is not an issue because the defense system requires just one sensor. The calculations for the range of values on the spider chart for the false-positive rate are based on the assumption that the defense system for a military building is active only during periods of high alert.



Scenario Summary

Enemy forces have deployed gas mines containing sulfur mustard as part of their coastal defenses. In preparation for an assault from the sea, friendly forces propel ruggedized, wireless, chemical sensors onto the beach from a standoff position. As the main body of troops prepares to land, the mines are detonated remotely (either by the enemy or with probes launched from the approaching vessels). The sensors detect the mustard gas and sound the alarm prior to the troop landing.

Scenario Details

Defense Posture

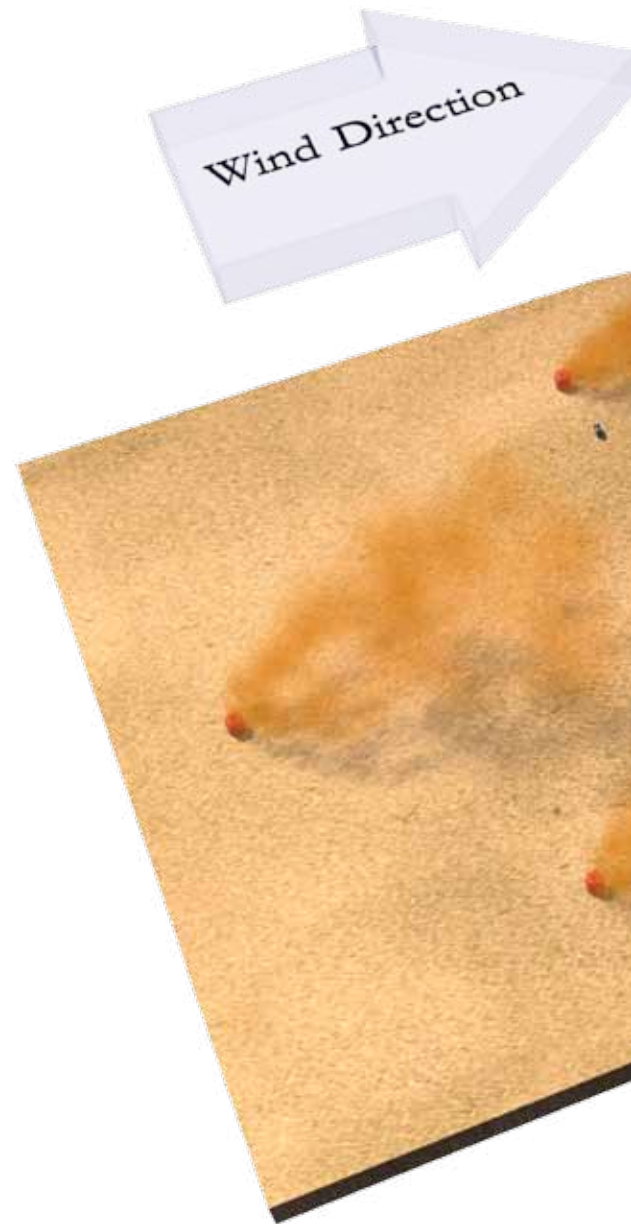
<i>Agent of Operation</i>	Beach assault
<i>Personnel Involved</i>	1 battalion
<i>Sensor Positions</i>	On beach parallel to water line
<i>Sensor To Protected Area Distance</i>	0.5 – 5 km
<i>Sensor Mission Duration</i>	6 hours per activation
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	Mustard gas
<i>Release Type</i>	Multiple point release from land mines
<i>Release Mass</i>	10 – 20 kg total
<i>Release Distance From Sensors</i>	50 – 200 m

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.1 – 1 mg/m ³
<i>Sensor Spacing</i>	50 – 100 m
<i>Sensor Response Time</i>	1 - 30 min

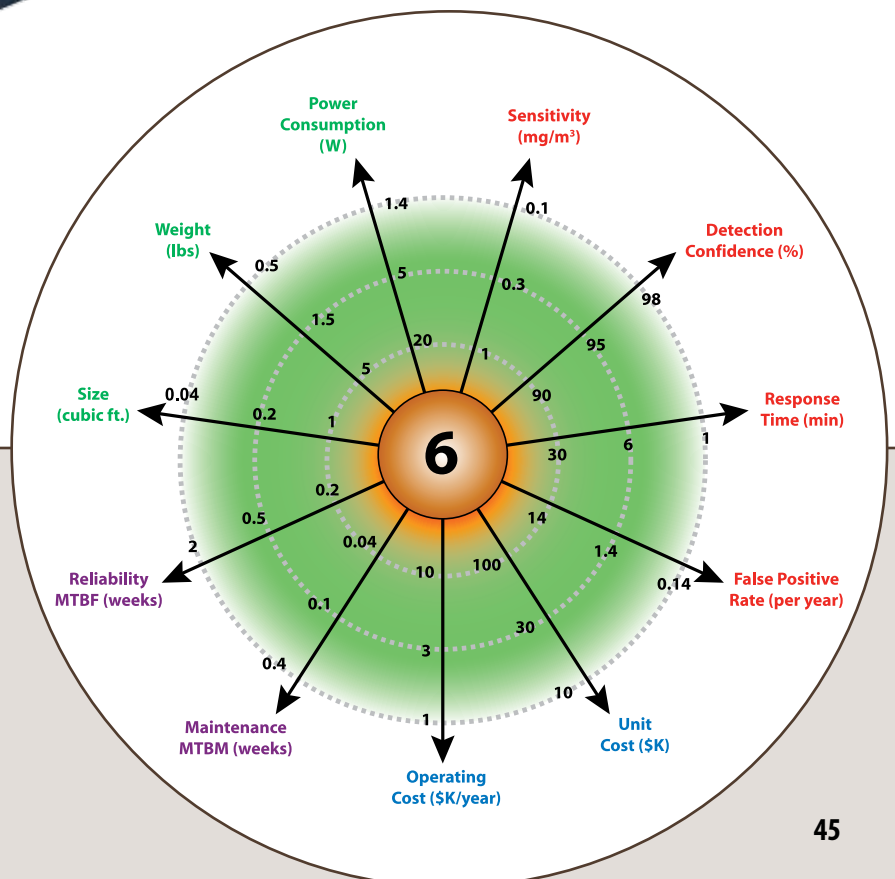
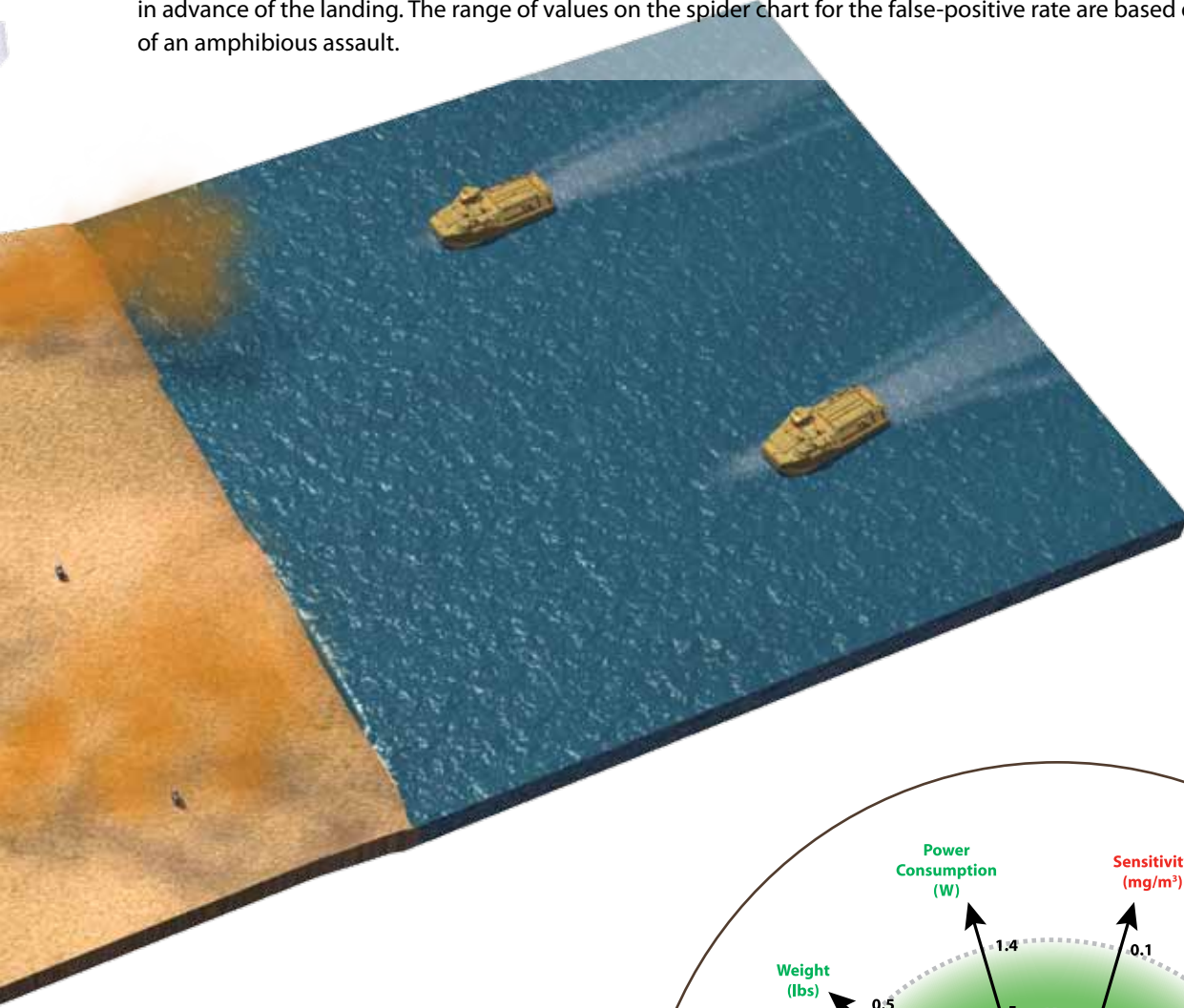


5.6 Amphibious Operation (Chemical/Multiple Point Release)

Scenario Results

The calculations show that the expected distribution of the mustard gas consists of tenuous clouds emanating from the mines and spreading across the expanse of beachfront. Detection of the dispersed vapor requires high sensitivity. The spacing of the sensors is determined by the wind conditions and atmospheric turbulence.

According to the description of the scenario, response time is not an issue because mine sweeping techniques were utilized in advance of the landing. The range of values on the spider chart for the false-positive rate are based on the high-alert status of an amphibious assault.



Scenario Summary

Enemy forces launch a missile attack on a friendly, forward airbase. The missiles release bomblets containing VX, a persistent nerve gas. The devices detonate in the air and release the toxic chemical along runways and onto operational areas. As part of the airbase's defense plan, point sensors have been deployed around the perimeter and within the base. The VX gas is detected by one or more of the sensors and the system sounds the alarm.

Scenario Details

Defense Posture

<i>Agent of Operation</i>	OCONUS Airbase
<i>Personnel Involved</i>	5,000 personnel
<i>Sensor Positions</i>	On airbase
<i>Sensor To Protected Area Distance</i>	1 – 100 m
<i>Sensor Mission Duration</i>	4 hours per activation
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	VX
<i>Release Type</i>	Multiple point release from missile attack
<i>Release Mass</i>	800-kg per missile (four missiles)
<i>Release Distance From Sensors</i>	0 – 1 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.01 – 2 mg/m ³
<i>Sensor Spacing</i>	25 – 100 m
<i>Sensor Response Time</i>	0 - 3 min



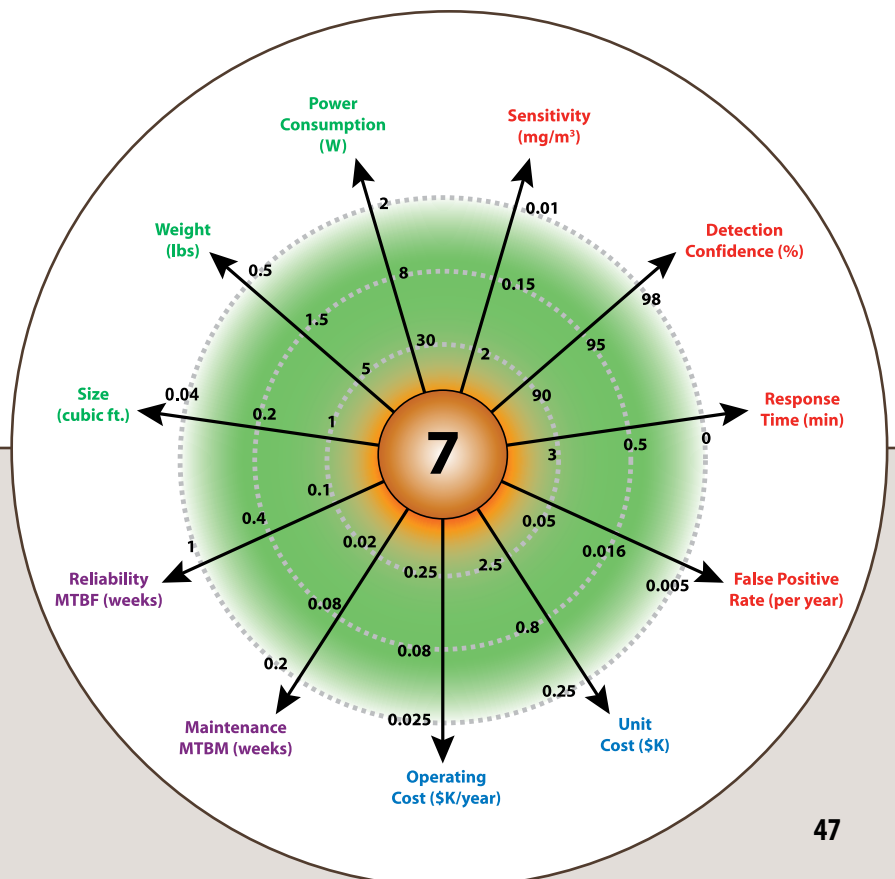
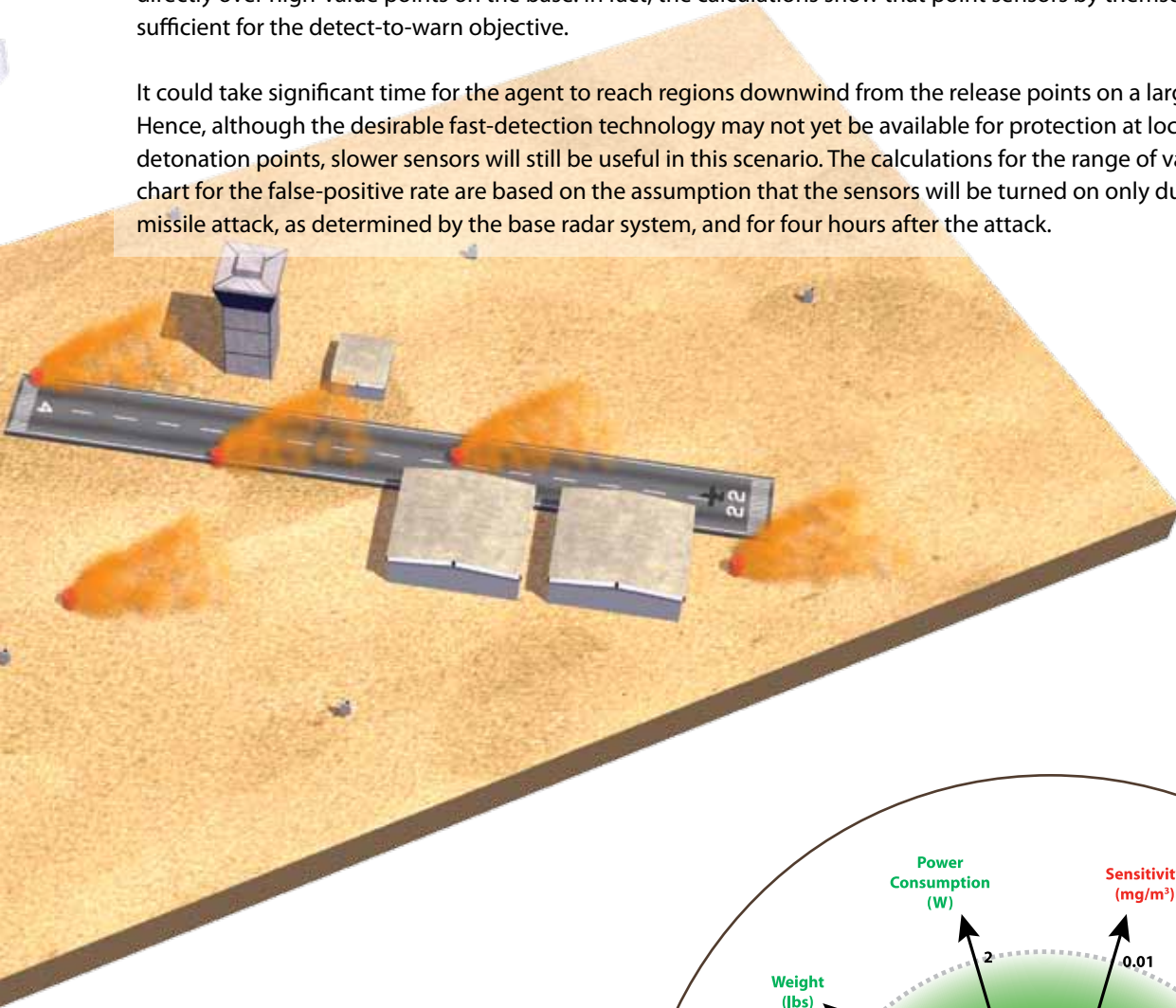
5.7

OCONUS Forward Airbase (Chemical/Multiple Point Release)

Scenario Results

The base will require an array of fast sensors that blanket the region of interest in order to provide detect-to-warn protection against the missile attack. Extremely high sensitivity is needed for the tenuous clouds of agent that will survive the delivery system and propagate downwind from the delivery points. Close spacing of the detectors is dictated by the random, scattered delivery pattern of the artillery shells. Extremely fast response times are needed because the rounds can detonate directly over high-value points on the base. In fact, the calculations show that point sensors by themselves are not completely sufficient for the detect-to-warn objective.

It could take significant time for the agent to reach regions downwind from the release points on a large Air Force base. Hence, although the desirable fast-detection technology may not yet be available for protection at locations close to the detonation points, slower sensors will still be useful in this scenario. The calculations for the range of values on the spider chart for the false-positive rate are based on the assumption that the sensors will be turned on only during the time of a missile attack, as determined by the base radar system, and for four hours after the attack.



Scenario Summary

Friendly forces are pursuing the enemy as it attempts to disengage from a battle. To cover their retreat, the enemy forces launch several mortar rounds containing VX, a persistent nerve gas, in an attempt to block the friendly forces path. The gas is detected by the point sensors mounted on the leading vehicles. A warning is transmitted to the main body of the advancing friendly forces. Pursuit is resumed after a delay of 2 minutes for the time required to take protective measures.

Scenario Details

Defense Posture

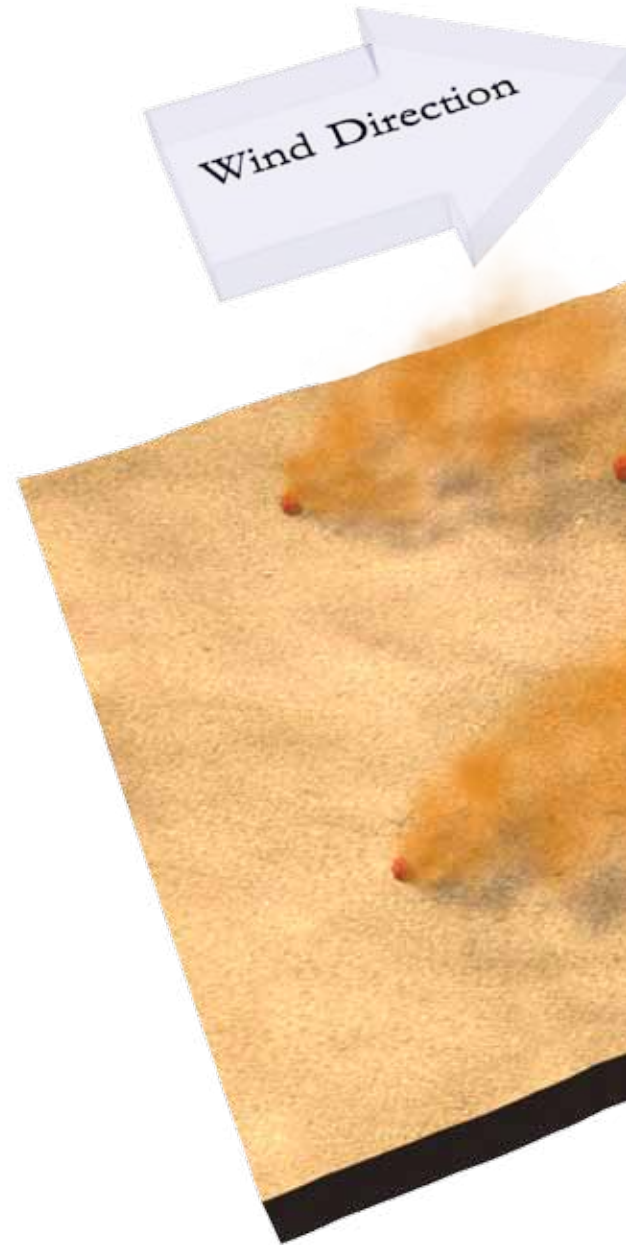
<i>Agent of Operation</i>	Main approach along road network in pursuit of retiring enemy forces
<i>Personnel Involved</i>	Military
<i>Sensor Positions</i>	On lead vehicles
<i>Sensor To Protected Area Distance</i>	0 – 10 km
<i>Sensor Mission Duration</i>	2 hours after detection of mortar attack
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	VX
<i>Release Type</i>	Multiple point release from mortar shells
<i>Release Mass</i>	1-kg per shell (three shells)
<i>Release Distance From Sensors</i>	0 – 1 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.1 - 10 mg/m ³
<i>Sensor Spacing</i>	1 sensor per lead vehicle
<i>Sensor Response Time</i>	0 - 3 min

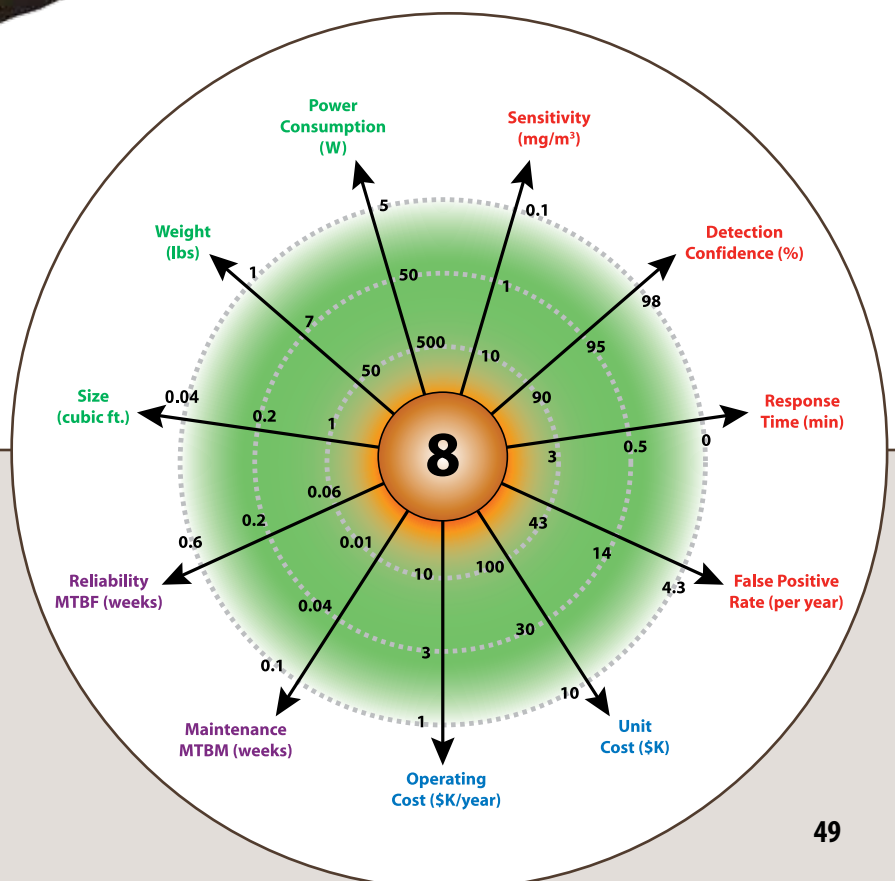
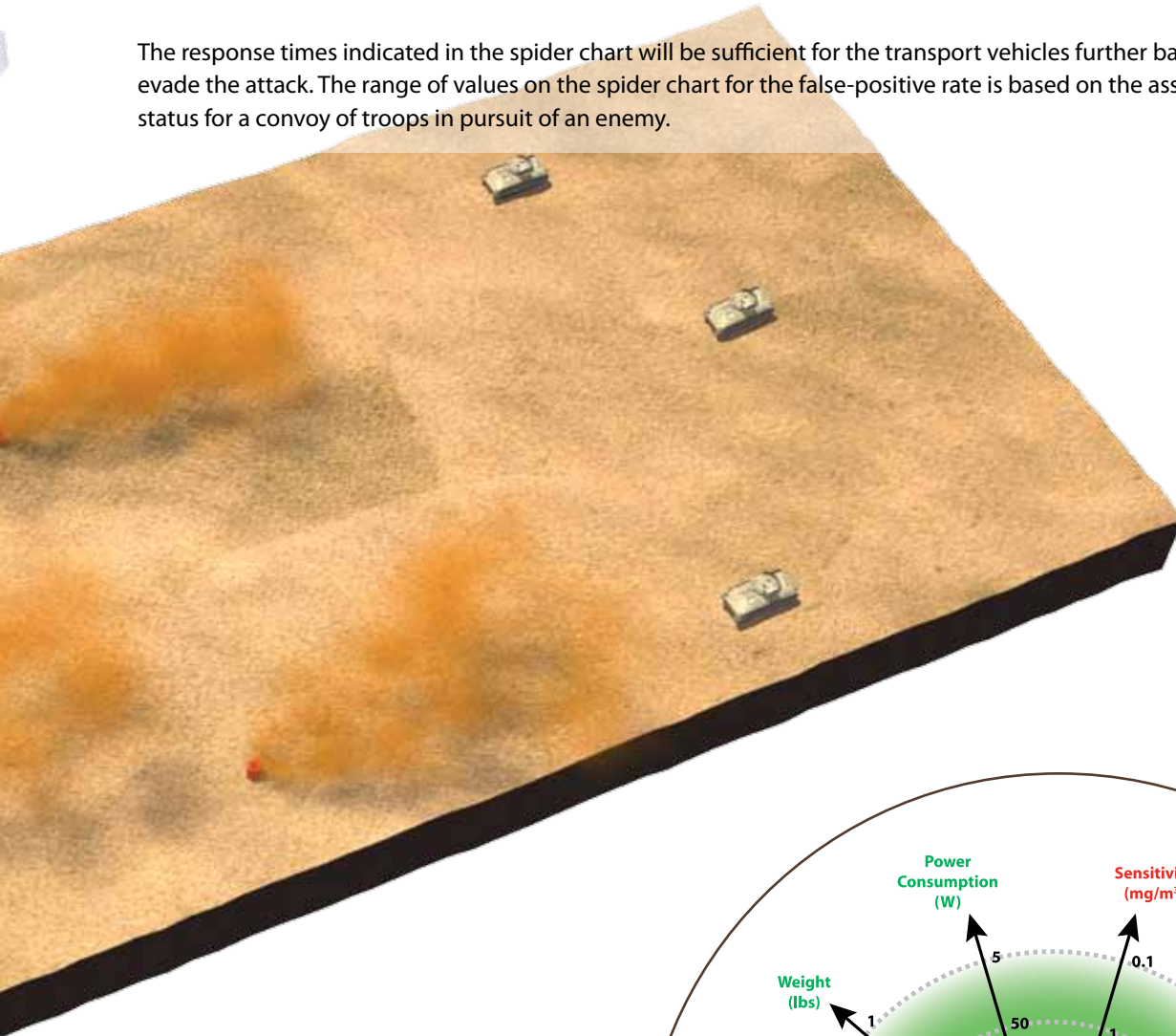


5.8 Terrain Denial (Chemical/Multiple Point Release)

Scenario Results

The mortar shells deposit the agent directly in front of the advancing friendly forces. Highly sensitive devices are required to detect the low concentrations of VX in the aerosol that will survive the delivery system and remain in the path of the pursuers. There will be no time for an adequate response for the occupants of the leading vehicles on which the sensors are presumed to be mounted. Indeed point sensors by themselves are not completely sufficient for the detect-to-warn objective for the protection of the lead forces.

The response times indicated in the spider chart will be sufficient for the transport vehicles further back in the convoy to evade the attack. The range of values on the spider chart for the false-positive rate is based on the assumption of a high-alert status for a convoy of troops in pursuit of an enemy.



Scenario Summary

Several terrorists have joined a grounds-maintenance crew and gone to work on a major military base at a time when weather conditions are right for landscaping tasks. The terrorists carry dried *Bacillus anthracis* (anthrax) in compressed air sprayers hidden in their leaf blowers. After fanning out across the post, they simultaneously release the anthrax powder from their sprayers. As part of the base's defense plan, an array of sensors has been deployed along the perimeter and within the base. The open air release is detected by one or more of the point sensors and the system sounds the alarm.

Scenario Details

Defense Posture

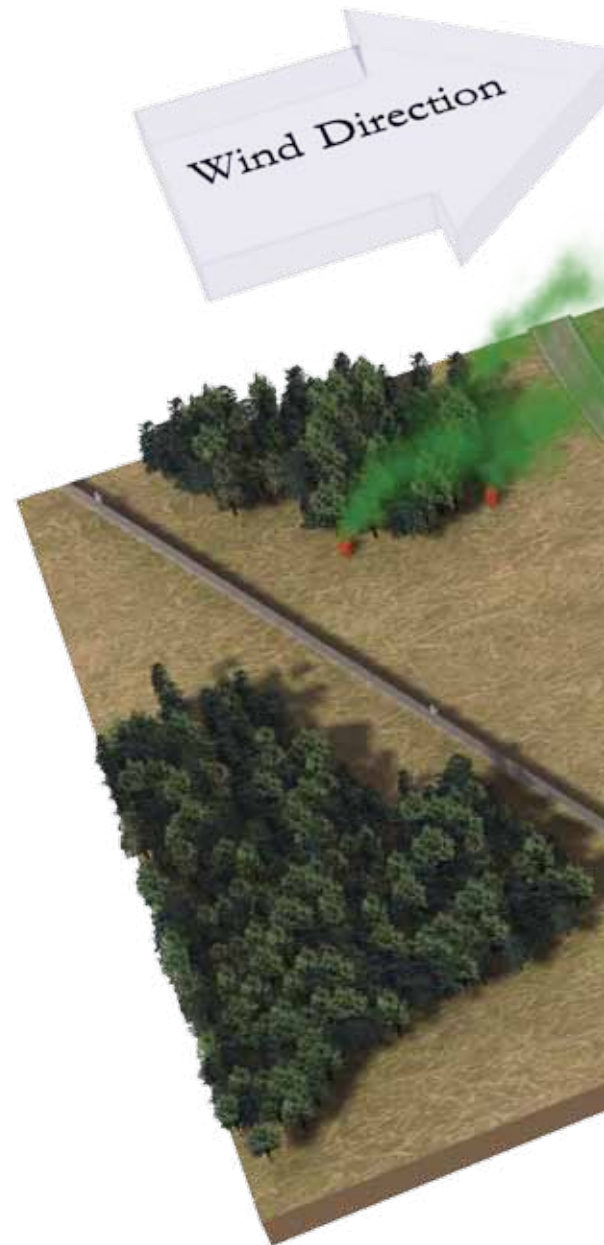
<i>Agent of Operation</i>	Large CONUS military base
<i>Personnel Involved</i>	20,000 personnel
<i>Sensor Positions</i>	Distributed on and within base perimeter
<i>Sensor To Protected Area Distance</i>	0 – 10 km
<i>Sensor Mission Duration</i>	One month per year
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	<i>Bacillus anthracis</i> (anthrax)
<i>Release Type</i>	Multiple point release from stationary sprayers
<i>Release Mass</i>	30 kg per sprayer (three sprayers)
<i>Release Distance From Sensors</i>	0 – 10 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.1 – 1 ppl
<i>Sensor Spacing</i>	50 – 100 m
<i>Sensor Response Time</i>	0 - 10 min

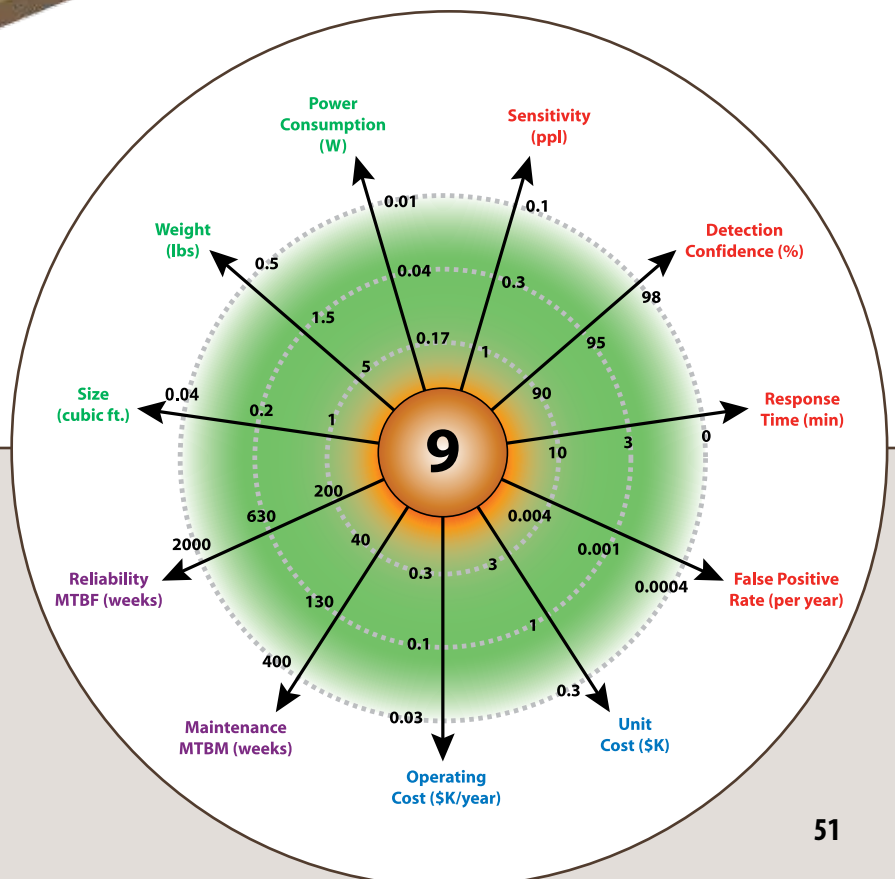
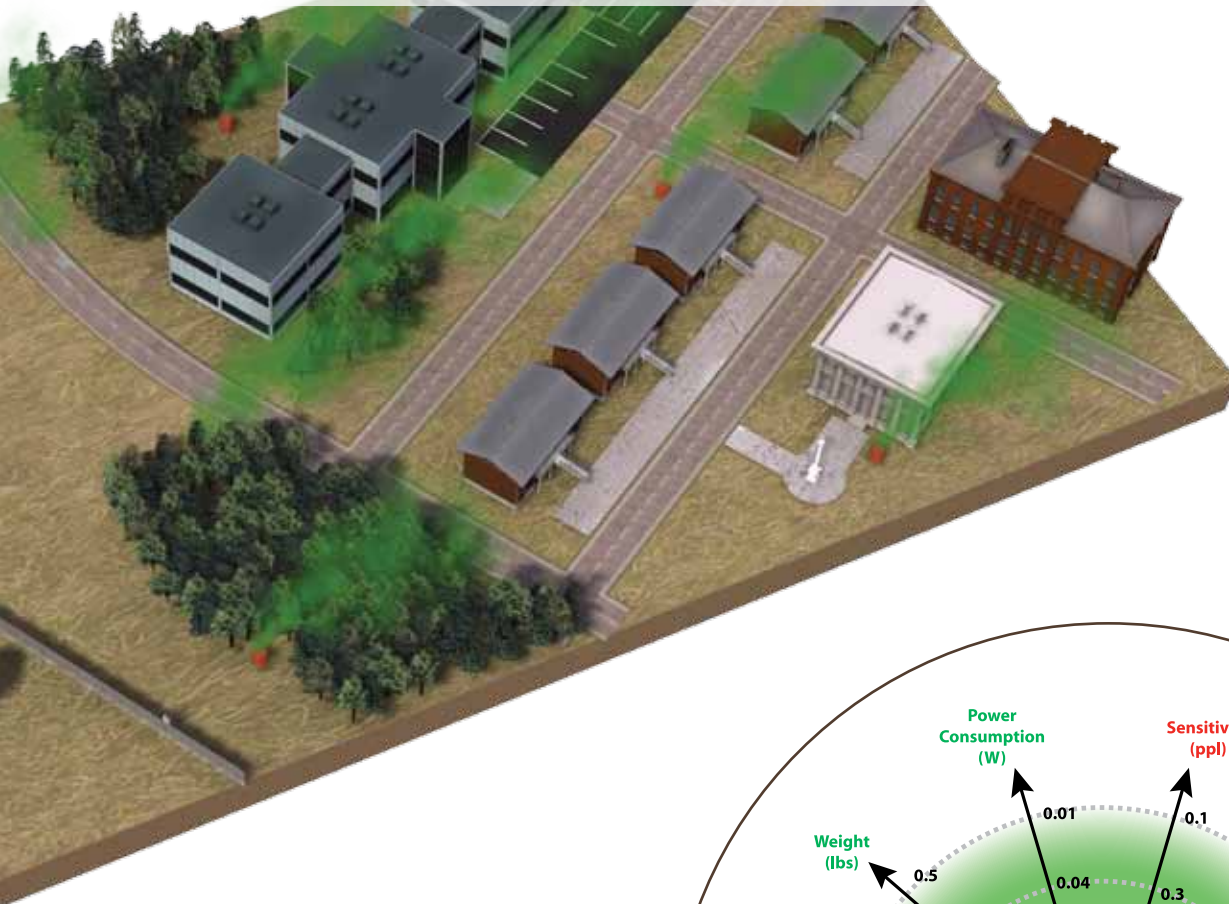


5.9 CONUS Military Post (Biological/Multiple Point Release)

Scenario Results

Highly sensitive devices are needed to detect the tenuous clouds propagating from the hand-held blowers under the atmospheric conditions that prevail when the groundskeepers are at work. High sensitivity is also required because the concentration remaining at ground level will be low for large as well as small payloads. The random distribution of the points of attack will require numerous closely spaced sensors blanketing the grounds to provide comprehensive protection against the clandestine nature of an attack that can occur anywhere on the military post. The point sensors by themselves are not completely sufficient for the detect-to-warn objective.

While evasion is not an option in the immediate vicinity, moderately fast response times are needed for the benefit of personnel located downwind from the multiple release points. The calculations for the range of values on the spider chart for the false-positive rate are based on the assumption that the system will be active only during times of high alert.



Scenario Summary

A group of terrorists has procured a crop duster. They have modified the aircraft's sprayer to make it capable of disseminating an aerosol containing *Bacillus anthracis* (anthrax). In the late evening, under meteorological conditions favorable for an attack, the biological agent is released from the plane on a path upwind of a major military installation. To avoid attracting the attention of the sentries on the base, the pilot maintains a safe distance from the perimeter which necessitates a release altitude of 50 meters for the aerosol to reach the intended target. Point detectors on the boundary of the base and surrounding critical assets detect the contaminant in the air and sound the alarm.

Scenario Details

Defense Posture

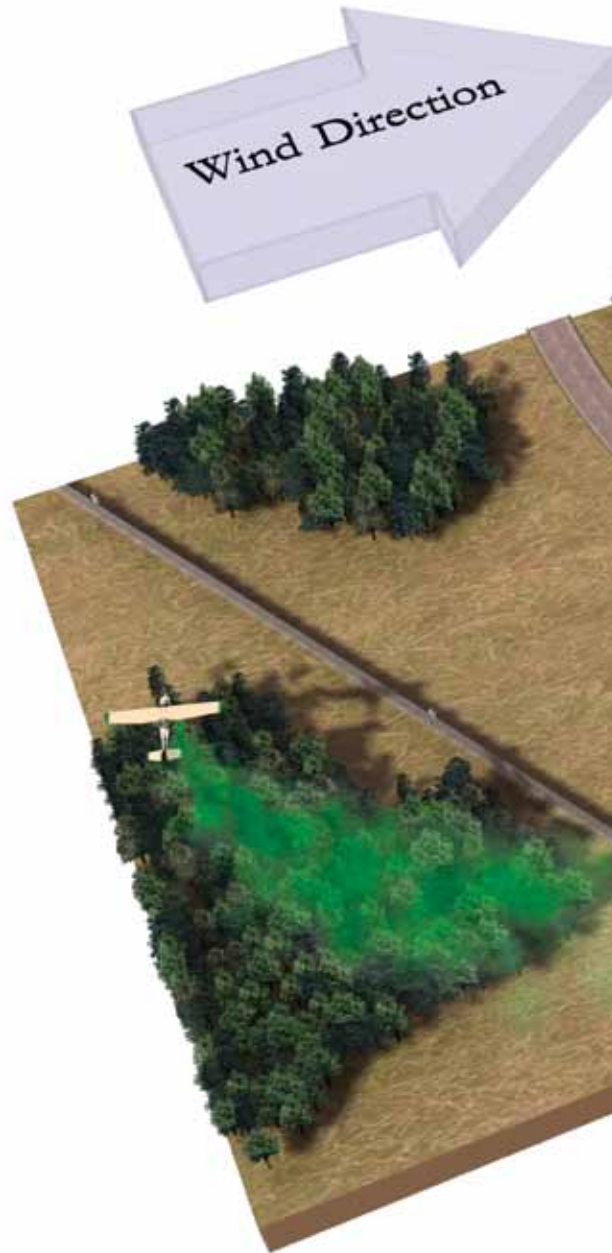
<i>Agent of Operation</i>	Large CONUS military base
<i>Personnel Involved</i>	14,000 personnel
<i>Sensor Positions</i>	Distributed on and within base perimeter
<i>Sensor To Protected Area Distance</i>	0 – 10 km
<i>Sensor Mission Duration</i>	One month per year
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	<i>Bacillus anthracis</i> (anthrax)
<i>Release Type</i>	Line release from crop duster
<i>Release Mass</i>	1 to 10 kg
<i>Release Distance From Sensors</i>	0 – 10 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.1 – 25 ppl
<i>Sensor Spacing</i>	500 – 1000 m
<i>Sensor Response Time</i>	1 - 7 min



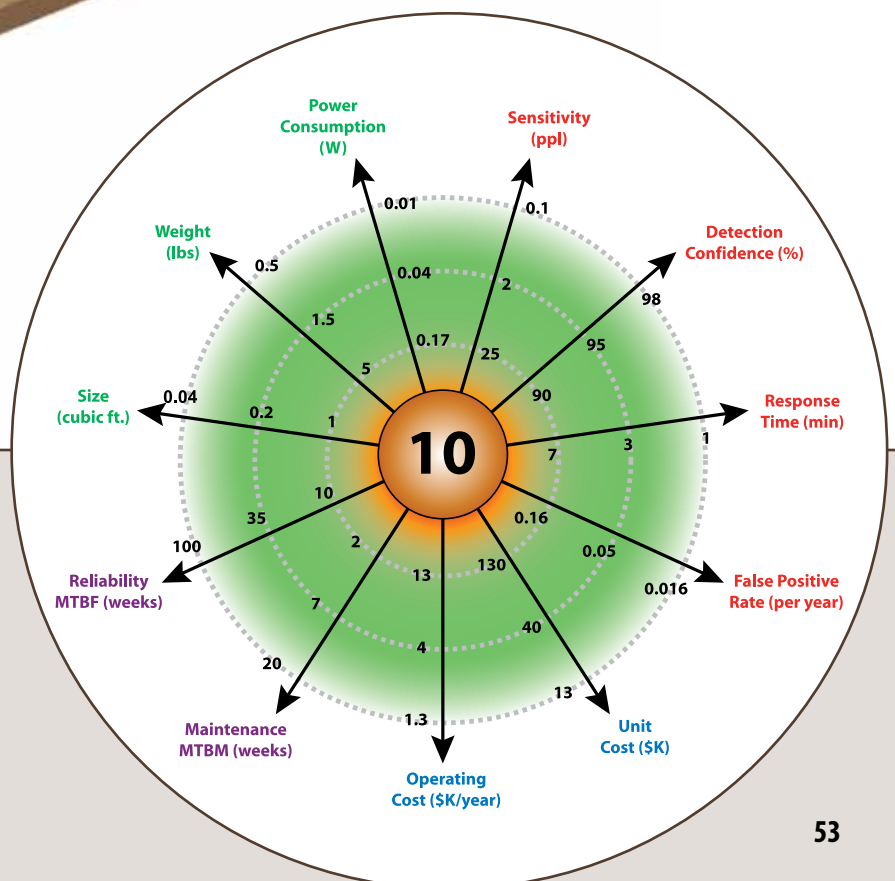
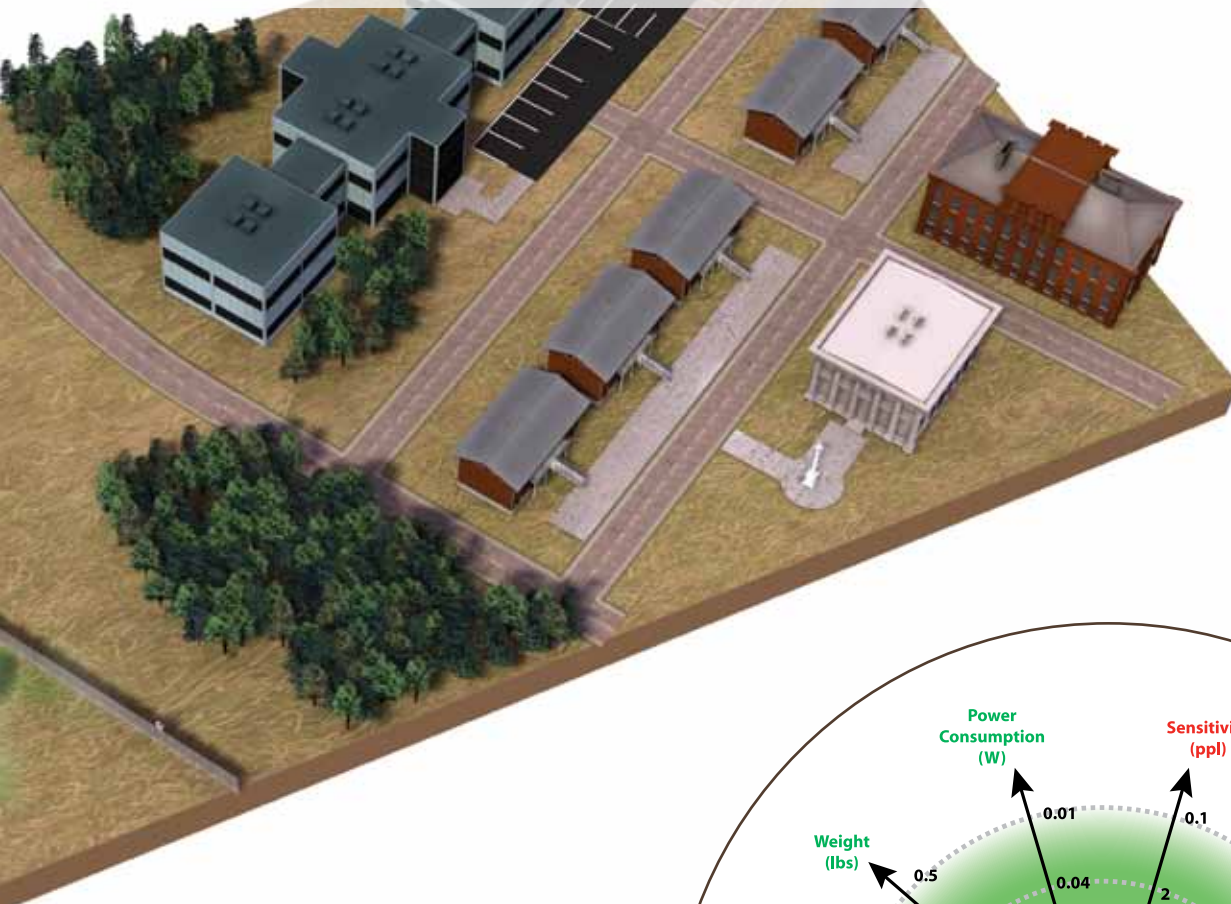
5.10

CONUS Military Post (Biological/Line Release)

Scenario Results

A small number of highly sensitive devices is sufficient and necessary to detect the line attack from the airplane release. The sensors do not have to be closely spaced because the mode of attack will generate a broad distribution of the agent in tenuous clouds. Sufficient separation from the release is enforced by restricting the air space and by positioning the sensors along the perimeter at a distance of one to two kilometers from the protected area, thereby reducing the requirements for a rapid response.

In some cases, the expected propagation will largely overfly the base perimeter and reach ground level within the military post. Under such meteorological conditions, detection will require extremely demanding sensitivities as indicated in the above table of results. The range of values on the spider chart for the false-positive rate are based on the assumption that the system will be active only during times when intelligence considerations call for a status of high alert.



Scenario Summary

Friendly combat forces in a defensive position have deployed chemical sensors along the perimeter of their location. Under meteorological conditions favorable for a chemical attack, enemy forces drive by on a path upwind of the defensive position and outside of the region of control. The enemy releases Sarin gas from a truck-mounted sprayer. The sensors detect the agent and sound the alarm. A warning is relayed immediately to the friendly forces and they take protective measures.

Scenario Details

Defense Posture

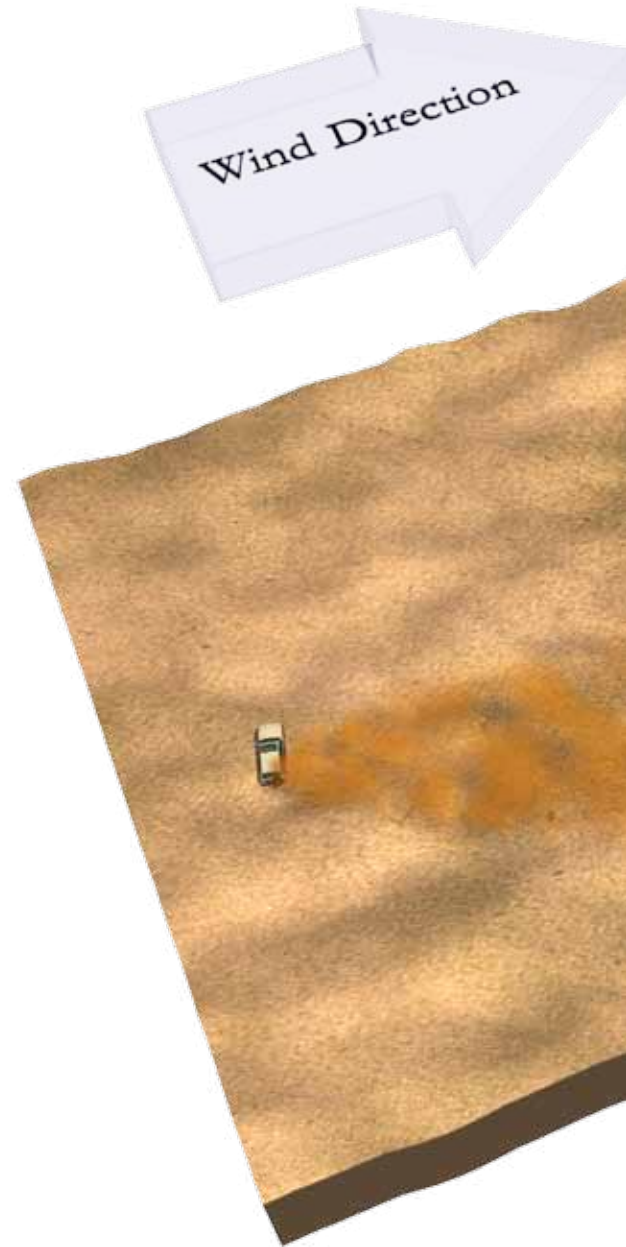
<i>Agent of Operation</i>	US combat forces defensive position
<i>Personnel Involved</i>	2,000 personnel
<i>Sensor Positions</i>	Upwind of defensive position
<i>Sensor To Protected Area Distance</i>	1.5 – 2 km
<i>Sensor Mission Duration</i>	24 hours
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	Sarin gas
<i>Release Type</i>	Line release from truck mounted sprayer
<i>Release Mass</i>	225 kg
<i>Release Distance From Sensors</i>	0.5 – 8 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.1 – 2 mg/m ³
<i>Sensor Spacing</i>	500 – 1000 m
<i>Sensor Response Time</i>	1 - 6 min



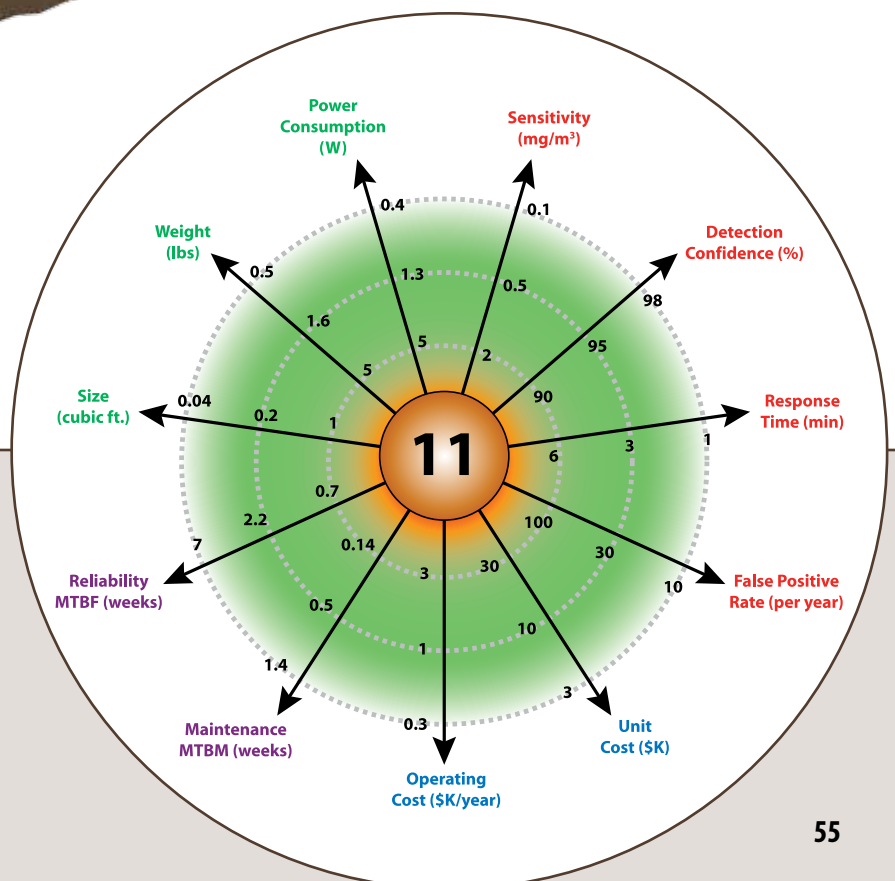
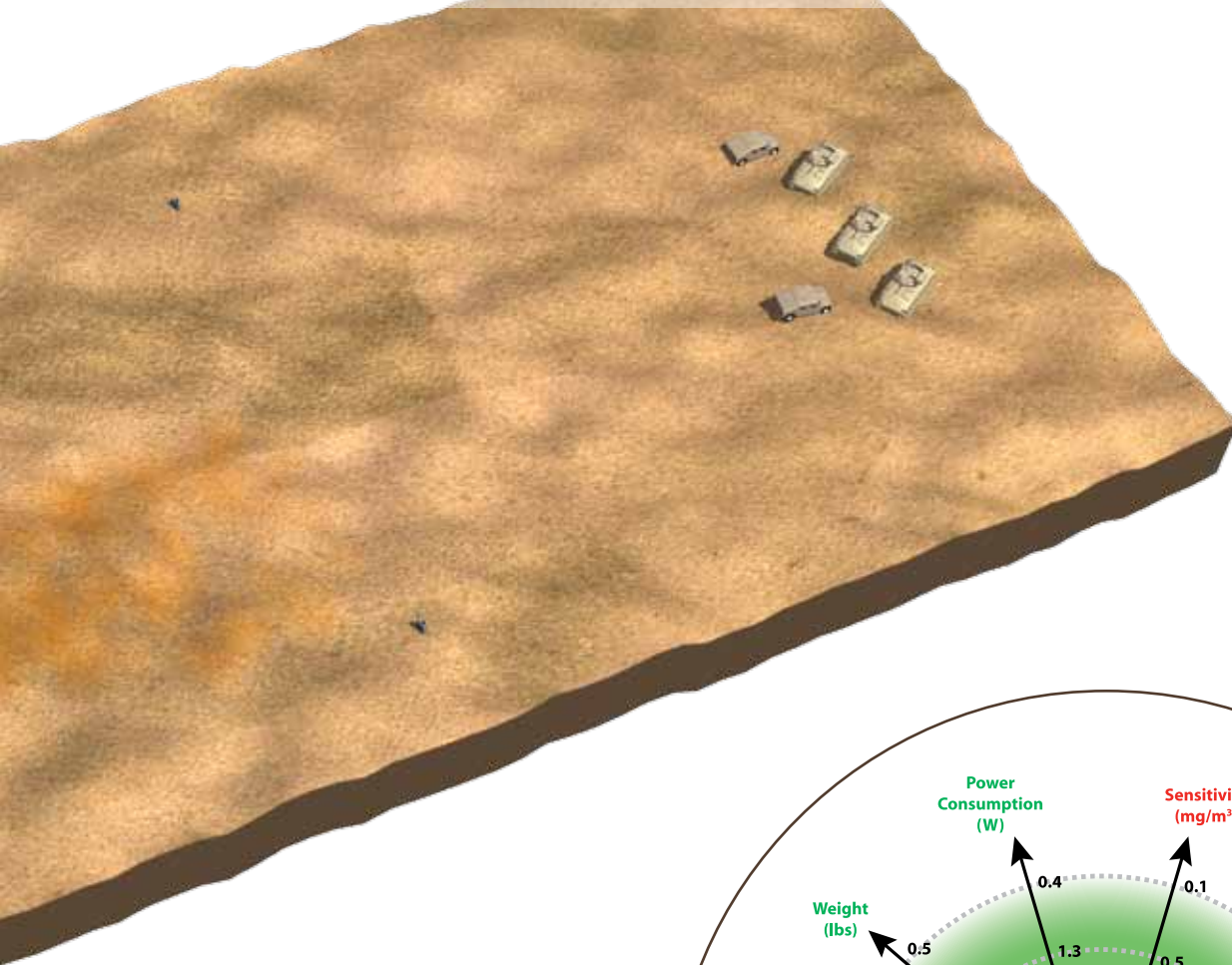
5.11

Defensive Positions (Chemical/Line Release)

Scenario Results

Extremely high sensitivity is needed to protect the troops against the line attack with the chemical agent in this scenario. Close spacing of the sensors is not a requirement. The mode of attack will generate a broad distribution of the Sarin gas in tenuous clouds.

A separation of one to two kilometers between the array of sensors on the perimeter of the region of control and the defensive position of the Army brigade is needed for a response time sufficient for the troops to don MOPP gear (mission-oriented protective posture). The range of values on the spider chart for the false-positive rate is based on the assumption of a high-alert status for troops in a defensive position.



Scenario Summary

Friendly combat forces have taken a defensive position and deployed detectors for biological agents upwind of their location. Under meteorological conditions favorable for a biological attack, enemy forces release a plume of *Bacillus anthracis* (anthrax) from an aircraft-mounted sprayer. To avoid attracting the attention of the sentries, the pilot maintains a discrete distance which necessitates a release altitude of 150 meters and a large payload in the weapon. The sensors detect the agent and sound the alarm. The warning is relayed immediately to the potentially affected forces allowing them to take protective measures.

Scenario Details

Defense Posture

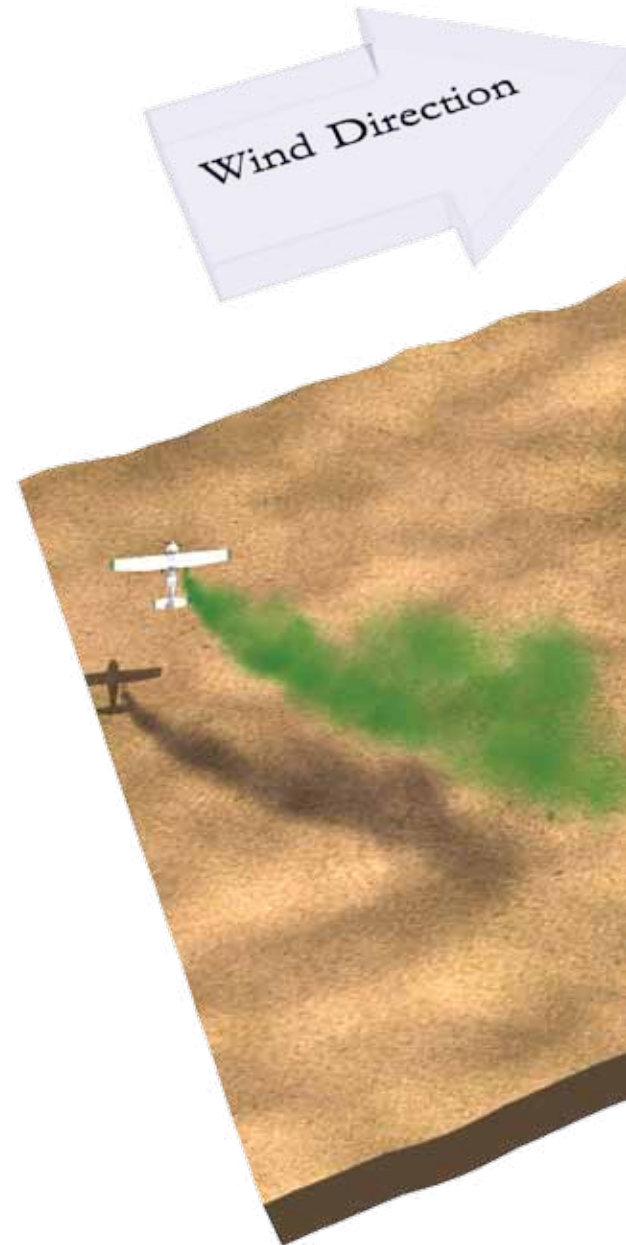
<i>Agent of Operation</i>	US combat forces defensive position
<i>Personnel Involved</i>	2,000 personnel
<i>Sensor Positions</i>	Upwind of defensive position
<i>Sensor To Protected Area Distance</i>	1.5 – 2 km
<i>Sensor Mission Duration</i>	24 hours
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	<i>Bacillus anthracis</i> (anthrax)
<i>Release Type</i>	Line release from low flying aircraft
<i>Release Mass</i>	1 - 10 kg
<i>Release Distance From Sensors</i>	0.5 – 8 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	0.1 – 10 ppl
<i>Sensor Spacing</i>	500 – 1000 m
<i>Sensor Response Time</i>	0 - 2 min



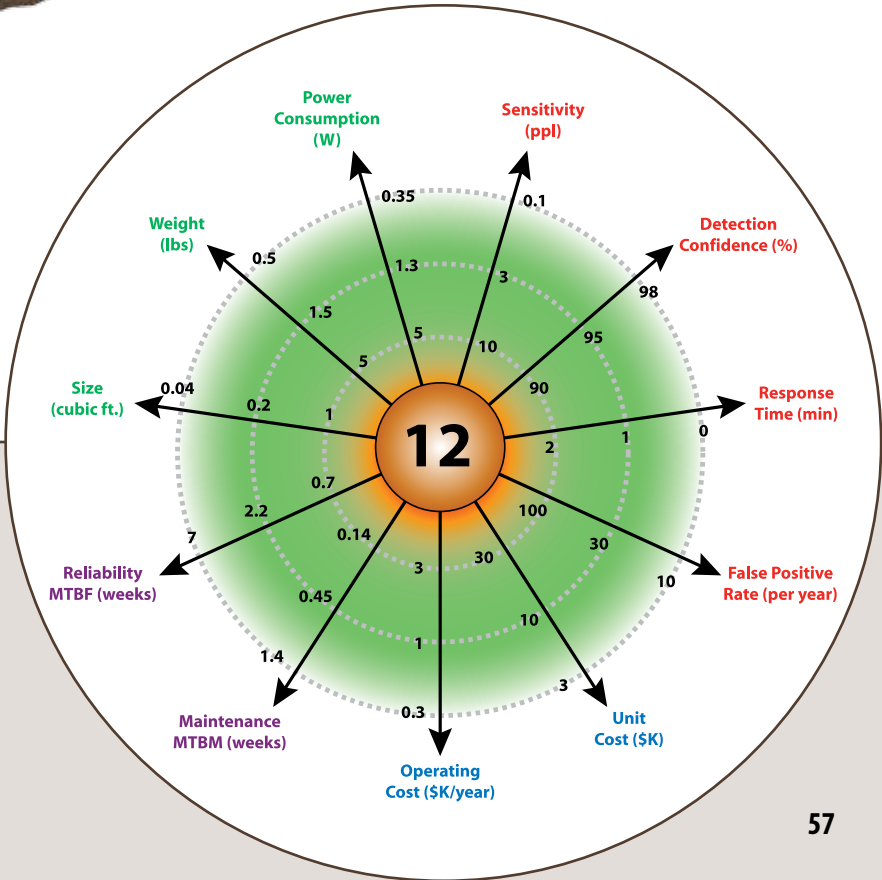
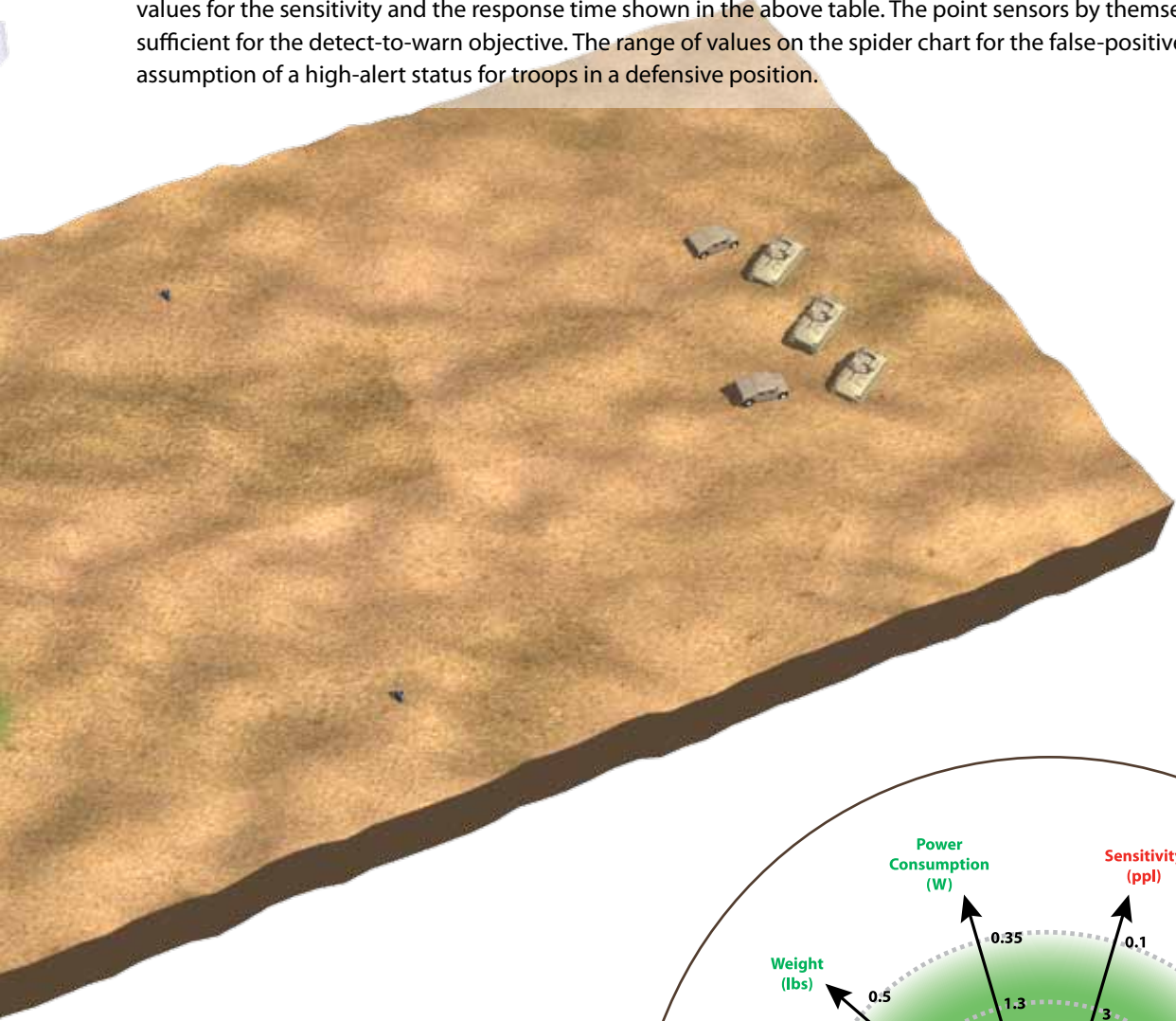
5.12

Defensive Positions (Biological/Line Release)

Scenario Results

Widely spaced but highly sensitive detectors are sufficient and required for the tenuous, broadly disbursed particles in the expected distribution from the distant aircraft.

The expected concentrations at the location of the sensors will be low but still high enough to deliver lethal doses to personnel located further downwind. Under such meteorological conditions, detection will require the extremely demanding values for the sensitivity and the response time shown in the above table. The point sensors by themselves are not completely sufficient for the detect-to-warn objective. The range of values on the spider chart for the false-positive rate is based on the assumption of a high-alert status for troops in a defensive position.



Scenario Summary

A terrorist group releases *Bacillus anthracis* (anthrax) from a truck-mounted sprayer while moving along a road upwind of a naval station. The plume travels over the base, around buildings, and over ships docked at the piers. Point sensors positioned around the perimeter of the base detect the agent and sound the alarm.

Scenario Details

Defense Posture

<i>Agent of Operation</i>	OCONUS Naval Port
<i>Personnel Involved</i>	6,000 personnel
<i>Sensor Positions</i>	Along port perimeter
<i>Sensor To Protected Area Distance</i>	0 – 4 km
<i>Sensor Mission Duration</i>	1 month per year
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	<i>Bacillus anthracis</i> (anthrax)
<i>Release Type</i>	Line release from truck mounted sprayer
<i>Release Mass</i>	225 kg
<i>Release Distance From Sensors</i>	0.5 - 8 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	1 – 500 ppl
<i>Sensor Spacing</i>	10 sensors along base perimeter
<i>Sensor Response Time</i>	0 – 7 min



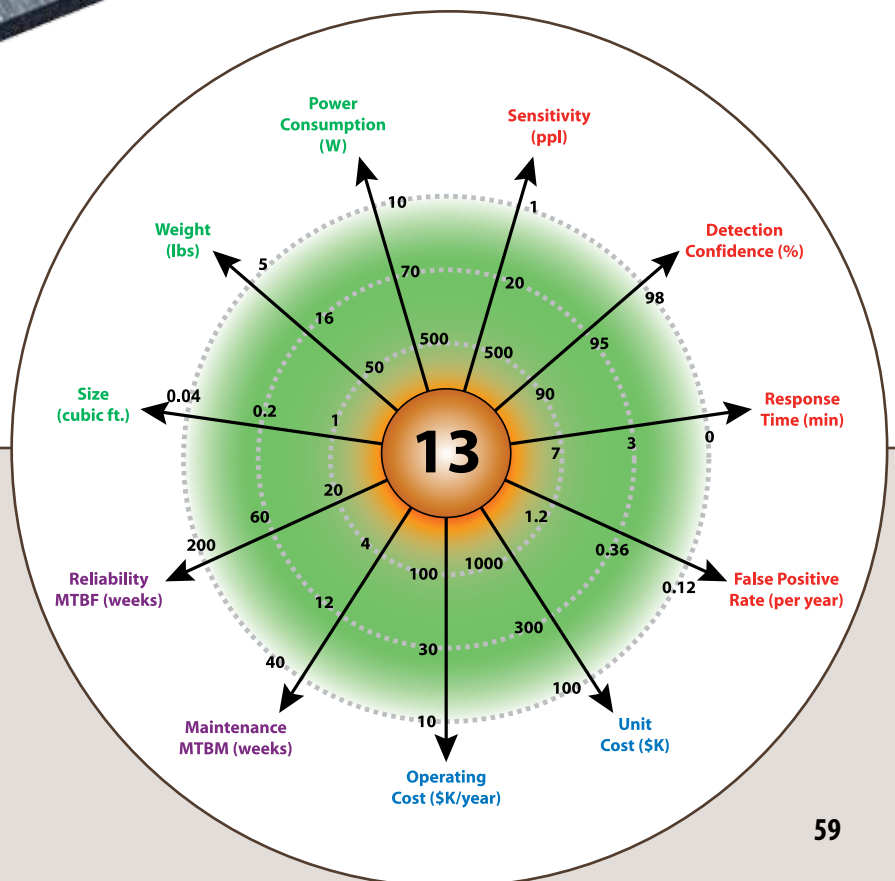
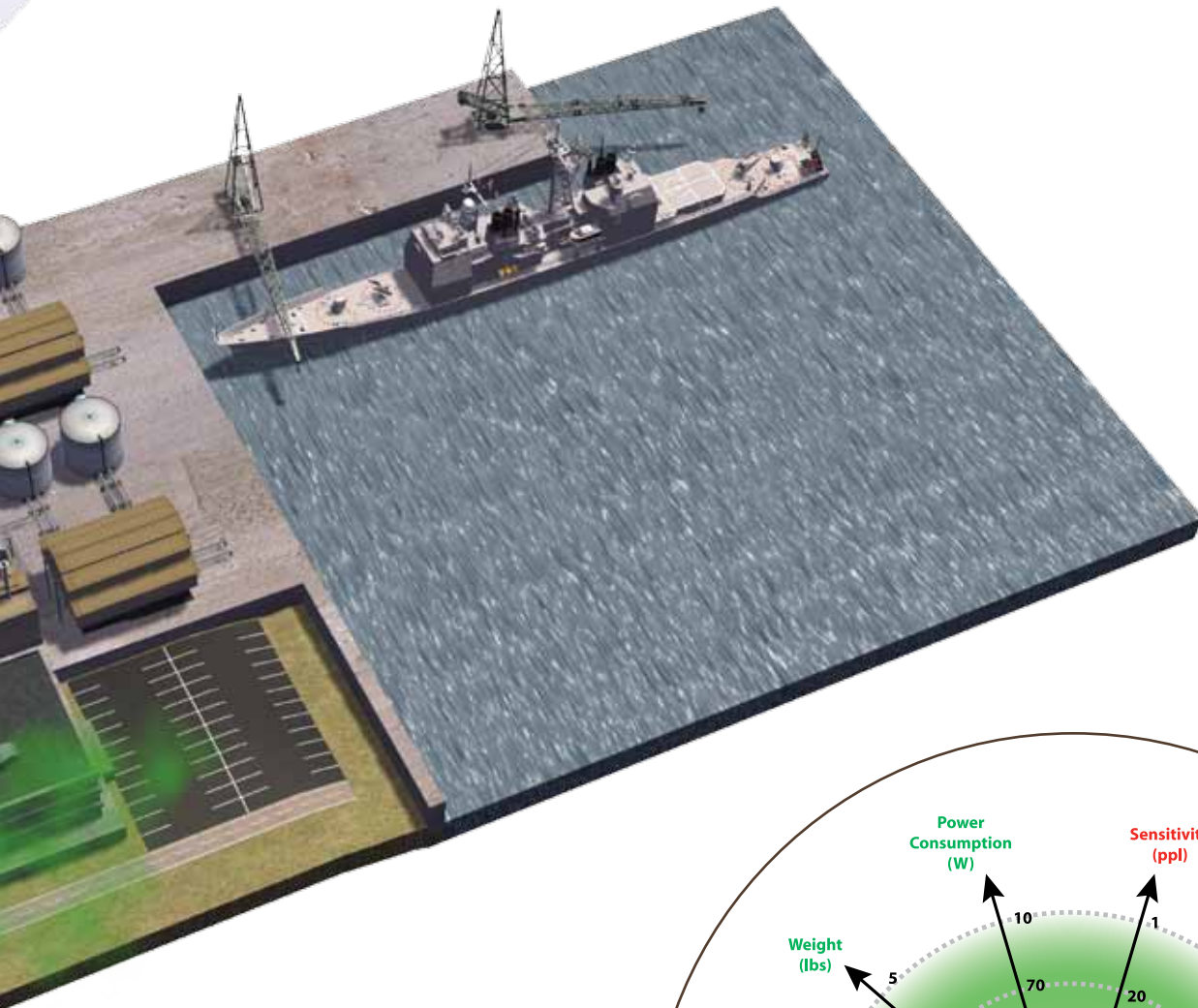
5.13

Naval Port Facility (Biological/Line Release)

Scenario Results

Highly sensitive devices are required to detect the tenuous distribution of the aerosol from the line attack.

Very short response times are required for the protection of the personnel close to the perimeter and the line attack. Response time is not an issue at locations further downwind on the docks or onboard ships in the harbor. The calculations for the range of values on the spider chart for the false-positive rate are based on the assumption that the system will be active only during times when considerations from intelligence sources call for a status of high alert.



Scenario Summary

A friendly naval ship is steaming into port. There are several fishing vessels in the harbor. A terrorist group releases a plume of *Yersinia pestis* (plague virus) into the wind from a boat-mounted sprayer. A cloud of the biological agent covers the ship. Sensors positioned on the deck detect the particles and sound the alarm.

Scenario Details

Defense Posture

<i>Agent of Operation</i>	Missile frigate
<i>Personnel Involved</i>	3,000 personnel
<i>Sensor Positions</i>	Along length of deck
<i>Sensor To Protected Area Distance</i>	0
<i>Sensor Mission Duration</i>	1 month per year
<i>Protective Response Time</i>	2 min

Attack Parameters

<i>Agent</i>	<i>Yersinia pestis</i> (plague virus)
<i>Release Type</i>	Line release from moving boat
<i>Release Mass</i>	225 kg
<i>Release Distance From Sensors</i>	0.5 – 8 km

Multirealization Scenario Analysis

<i>Sensor Sensitivity</i>	1 – 500 ppl
<i>Sensor Spacing</i>	10 sensors on deck
<i>Sensor Response Time</i>	0 – 0.25 min



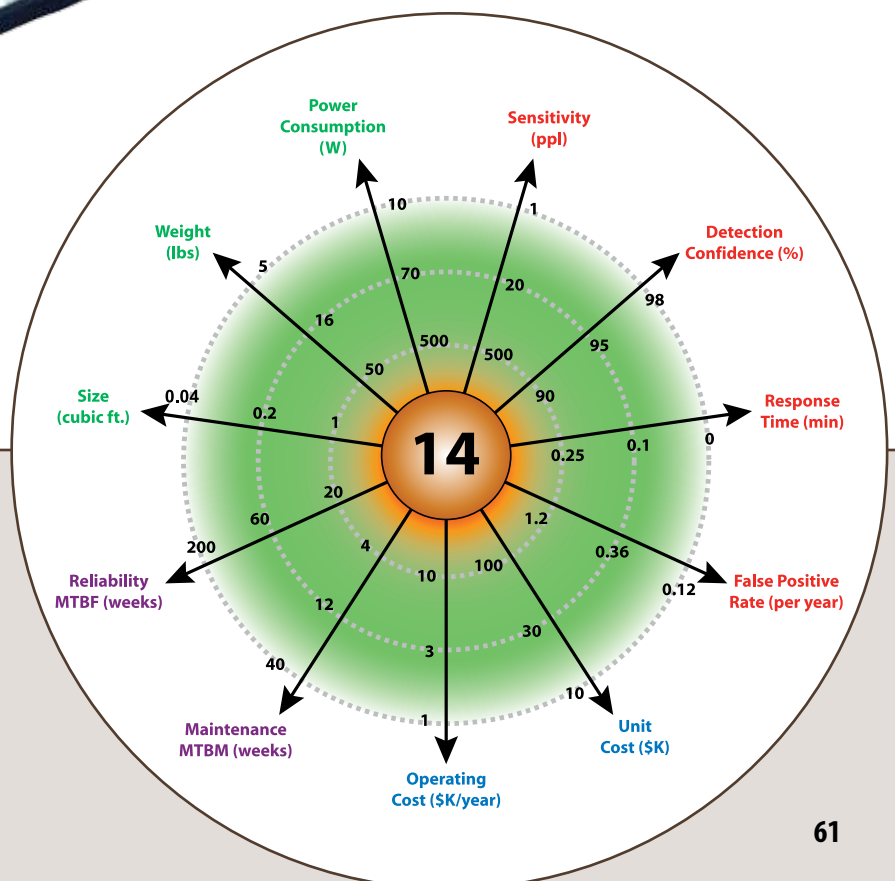
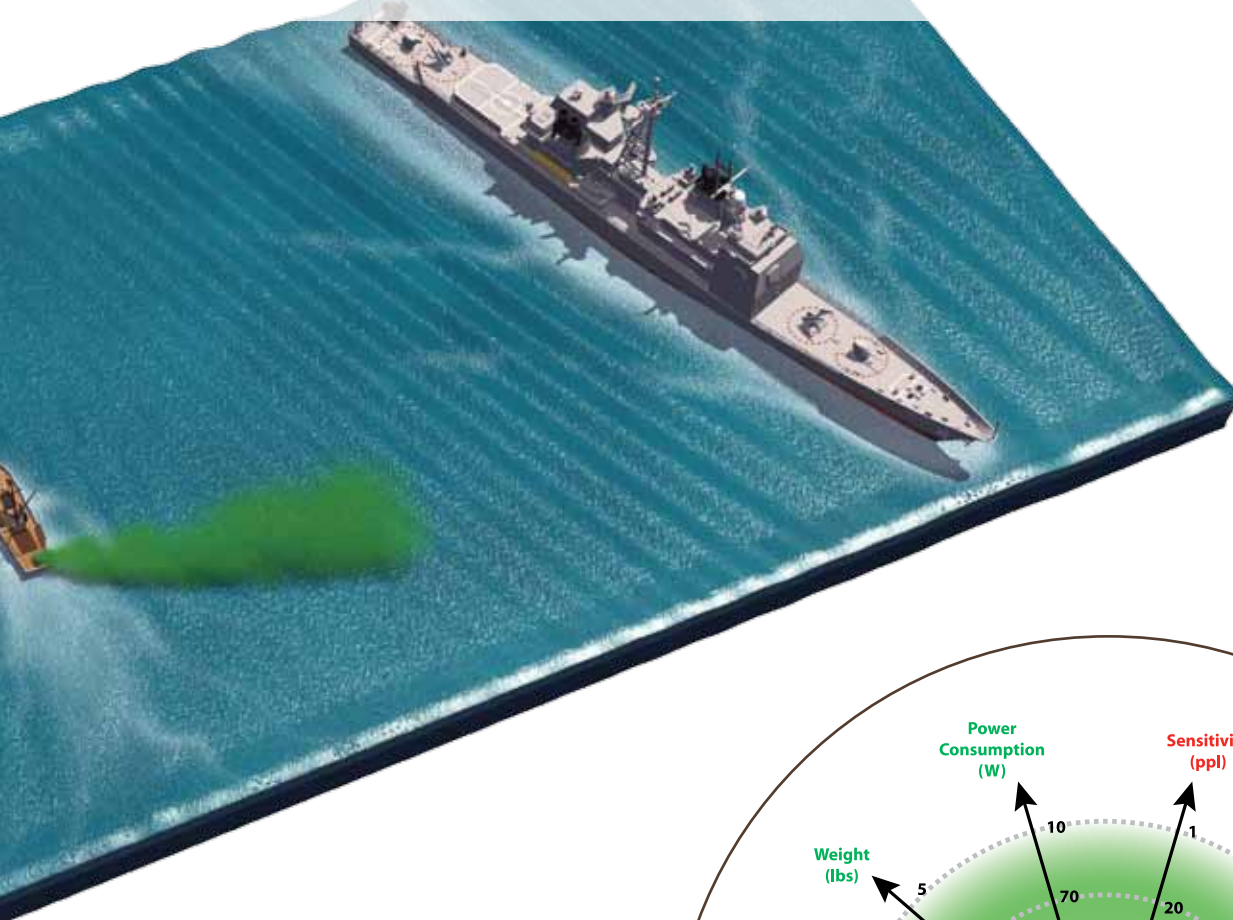
5.14

Naval Ship in Littoral (Biological/Line Release)

Scenario Results

The plume of particles containing the plague virus will engulf the sailors on the deck at the same time that it reaches the shipboard sensors. For them, the scenario allows for zero response time. Thus, point sensors by themselves cannot provide the complete solution for the detect-to-warn objective. A fast system response will be required for the protection of personnel located on deck. Also, a short response time is needed to stop the ventilation system from carrying the agent into the interior chambers of the ship.

Spatial limitations on the vessel and the need to minimize response time dictate close spacing of a small number of detectors. Moderately high sensitivity is needed to achieve a high probability of detection with just a few sensors. The calculations for the range of values on the spider chart for the False-Positive Rate take into account the presumed high-alert status of a ship in littoral with possibly unfriendly boats in the vicinity.



Scenario Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Scenario Name		1. Convoy Movement	2. Convoy Movement	3. Ground Forces Defense	4. Military Building (Internal attack)	5. Military Building (External attack)	6. Amphibious Operation	7. OCONUS Forward Airbase	8. Terrian Denial	9. CONUS Military Post	10. CONUS Military Post	11. Defense Positions	12. Defense Positions	13. Naval Port Facility)	14. Navy Ship in Littoral
1	Sensitivity (ppl or mg/m ³)	1	0.1	1	0.1	0.5	0.1	0.01	0.1	0.1	0.1	0.1	0.1	1	1
		20	1	20	30	16	0.3	0.15	1	0.3	2	0.5	0.3	20	20
		500	10	500	100	500	1	2	10	1	25	2	10	500	500
2	Detection Confidence (%)	98	98	98	98	98	98	98	98	98	98	98	98	98	98
		95	95	95	95	95	95	95	95	95	95	95	95	95	95
		90	90	90	90	90	90	90	90	90	90	90	90	90	90
3	Response Time (min)	1	1	1	0.1	0.1	1	0	0	0	1	1	0	0	0
		3	3	3	0.3	0.3	6	0.5	0.5	3	3	3	1	3	0.1
		10	10	10	1	1	30	3	3	10	7	6	2	7	0.25
4	False Positive Rate (per year) (during sensor operation)	.04	0.02	0.2	0.1	100	0.14	0.005	4.3	0.0004	0.016	10	10	0.12	0.12
		0.4	0.2	1	0.4	250	1.4	0.016	14	0.001	0.05	30	30	0.36	0.36
		4	2	2	1	500	14	0.05	43	0.004	0.16	100	100	1.2	1.2
5	Unit Cost (\$k)	0.025	0.1	7	10	100	10	0.25	10	0.3	13	3	3	100	10
		0.8	0.3	20	30	300	30	0.8	30	1	40	10	10	300	30
		2.5	1	70	100	1000	100	2.5	100	3	130	30	30	1000	100
6	Operating Cost (\$k/year)	0	0	0.7	1	10	1	0.025	1	0.03	1.3	0.3	0.3	10	1
		0	0	1	3	30	3	0.08	3	0.1	4	1	1	30	3
		0	0	7	10	100	10	0.25	10	0.3	13	3	3	100	10
7	Maintenance MTBM (operating weeks)	NA	NA	1.4	40	0.2	0.4	0.2	0.1	400	20	1.4	1.4	40	40
		NA	NA	0.44	13	0.08	0.1	0.08	0.04	130	7	0.5	0.5	12	12
		NA	NA	0.14	4	0.02	0.04	0.02	0.01	40	2	0.14	0.14	4	4

Table 5.15 Sensor key metric and other attribute requirements ranges for all scenarios.

- ☐ Diminishing Return Value
- ☐ Nominal Value
- ☐ Marginal Value

Scenario Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Scenario Name		1. Convoy Movement	2. Convoy Movement	3. Ground Forces Defense	4. Military Building (Internal attack)	5. Military Building (External attack)	6. Amphibious Operation	7. OCONUS Forward Airbase	8. Terrian Denial	9. CONUS Military Post	10. CONUS Military Post	11. Defense Positions	12. Defense Positions	13. Naval Port Facility)	14. Navy Ship in Littoral
8	Reliability MTBF (operating weeks)	4	0.06	7	200	1.2	2	1	0.6	2000	100	7	7	200	200
		1	0.02	2.2	63	0.38	0.5	0.4	0.2	630	35	2.2	2.2	60	60
		0.4	0.006	0.7	20	0.12	0.2	0.1	0.06	200	10	0.7	0.7	20	20
9	Size (cubic ft.)	0.04	0.04	0.04	0.04	1	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
		0.2	0.2	0.2	0.2	3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
		1	1	1	1	8	1	1	1	1	1	1	1	1	1
10	Weight (lbs)	1	1	1	1	10	0.5	0.5	1	0.5	0.5	0.5	0.5	5	5
		2	2	2	7	30	1.5	1.5	7	1.5	1.5	1.5	1.5	16	16
		5	5	5	20	100	5	5	50	5	5	5	5	50	50
11	Power Consumption (W)	0.1	9	0.4	1	100	1.4	2	5	0.01	0.01	0.4	0.35	10	10
		0.4	32	1.4	10	1000	5	8	50	0.04	0.04	1.3	1.3	70	70
		2	120	5	100	10000	20	30	500	0.17	0.17	5	5	500	500
12	Sensor Spacing (m)	50	50	50	One sensor in every return air duct	One sensor in roof-top HVAC intake	50	25	One sensor per lead vehicle	50	500	500	500	10 sensors along base perimeter	10 sensors along deck of ship
		160	70	70			70	50		70	700	700	700		
		500	100	100			100	100		100	1000	1000	1000		
13	Total number of sensors deployed	400	900	15	100	1	10	4000	10	3000	75	3	3	10	10
14	Total sensor-system cost (\$K)	100 - 1000	100 - 1000	100 - 1000	1000 - 10,000	100 - 1000	100 - 1000	1000 - 10,000	100 - 1000	1000 - 10,000	1000 - 10,000	10 - 100	10 - 100	1000 - 10,000	100 - 1000

Table 5.15 (continued) Sensor key metric and other attribute requirements ranges for all scenarios.

- ☐ Diminishing Return Value
- ☐ Nominal Value
- ☐ Marginal Value



6.0 SUMMARY

Phase I sought to address the inadequate evaluation of sensor performance metrics by proposing that ROC curves be used for the evaluation of CB sensors and described how to generate these curves to characterize sensor performance through a plot on the spider chart. Phase II was initiated to develop a methodology for determining sensor requirements.

The accomplishments of this study are:

- 1. Developed fourteen chemical and biological attack scenarios for the purpose of evaluating sensor requirements.**
- 2. Conducted a multirealization mathematical analysis in order to quantitatively determine the sensor requirements for sensitivity, response time, and deployment density for each scenario.**

- 3. Conducted a quantitative cost-benefit analysis in order to determine the false positive rate requirements for two scenarios.**
- 4. Constructed sensor requirement spider charts for each scenario that detail the minimally acceptable, nominal, and diminishing return values for the sensor key metrics as well as the other sensor attributes.**

While this study has produced significant findings, the Panel recognizes that there are a number of additional sensor evaluation issues that should be considered. Those additional subjects are detailed in Section 7.0.



7.0 PATH FORWARD

The scope of Phase I and II of the CBS3 Study were purposely limited to aerosol/vapor point detectors in primarily detect-to-warn scenarios. However, there are a number of other topics which warrant further analysis. These topics are:

- Standoff Sensors
- Confirmatory Sensors
- Networking of Sensors
- Sample Collectors
- Scenario Degradation
- Quantitative Analysis

Each of these areas are described in the following section.

Standoff Sensors

It is useful to first define a standoff sensor and differentiate it from a point detector. A point detector is one in which the sample undergoing testing is somehow confined, even if only very briefly, within the physical dimensions of the sensor itself. For example, the Joint Biological Point Detection System (JBPDS) interrogates particles within the system chassis. A standoff sensor, on the other hand, measures samples (such as aerosol particles or chemical vapors) by a variety of means, at some distance removed from the physical dimensions of the detection system itself. The Biological Standoff Detection System (BSDS) experimental system is one such example of a standoff bio-sensor in that it optically interrogates aerosol particles at ranges of several kilometers from the actual sensor system. Clearly, designing and building such a standoff system is typically more complex and challenging than a

point detection system with commensurate performance. As a single example, the measurement must take place over an extended distance and through an often turbulent and uncooperative atmosphere. Standoff sensors may provide earlier warning than point sensors that cannot be placed sufficiently upwind, however, standoff sensors typically do not provide as much discrimination as point sensors and may, therefore, have higher false positive rates.

Confirmatory Sensors

Confirmatory sensors are also referred to as “Identifiers” owing to their ability to provide, with varying degrees of fidelity, actual species identification of analytes under testing. These sensors are an essential component of an overall detection system, providing the capability to perform the “detect-to-treat” mission. Also, these sensors can, as their name suggests, confirm an actual attack with a high degree of assurance. Some confirmatory sensors also have the ability to provide quantitative results, the significance of which is discussed below under “Quantitative Analysis.” Many confirmatory sensors, especially in the case of bio-sensors, use wet chemistry. Pathogens from the air, on surfaces, or in liquid form (for example, from the water supply) must first be collected and put into an appropriate buffer solution for subsequent analysis. The need for sample collection motivates the desire to investigate collection technologies and techniques, as described under “Sample Collectors” below. Owing to their more complex construction compared to trigger detectors, a new set of analysis must be conducted to evaluate the performance of confirmatory sensors.

Networking of Sensors

The performance enhancements associated with the intelligent networking of sensors have already been introduced in this report. It is important to note that the manner in which sensors are networked can have a profound effect on performance; indeed, failure to properly network sensors can result in an overall performance degradation. On the other hand, properly taking into account air flow patterns (either from meteorological data or HVAC patterns) and requiring adjacent sensors to enter an alarm state in a predictable pattern before declaring an attack has occurred, can greatly reduce false positives.

Sample Collectors

Sample collectors are critical to performing actual species identification and follow-up forensic analysis. Although often overlooked as a more mundane issue, collectors can often be the key determinant for power consumption and response time for an overall sensor system. Sample collectors can, therefore, have a profound impact on the system-level spider chart footprint. Moreover, there have been recent advances in collector technologies, in particular approaches enabling ultra-miniaturization, which can have a positive impact on overall sensor system size and weight.

Scenario Degradation

Scenario “degradation” is defined in response to the question “How brittle are these scenarios?” In other words, how robust are the scenarios to account for changes in the nature of the attack, given that no matter how stringent the efforts are to determine the exact nature of a possible attack, perfect prescience will never be achieved. As a result, effort should be directed toward investigating how susceptible a given scenario is to change, and how the scenario outcome is dependent on changes to various input variables. This is tantamount to a “mathematical error analysis” in which one looks at which input variables have the greatest impact on the out variable.

Quantitative Analysis

Although there is much utility in providing early warning of a potential CB attack, there is even greater efficacy if the sensor can also give an estimate of the relative magnitude of the attack. Imagine for a moment the differing response a Brigade commander would execute if told that the attack on the Brigade support area was a mere 1 gram of anthrax compared to the actions he would take if the attack were known to be 1 kilogram of anthrax. First, simply knowing the magnitude of the attack will surely impact the confidence the commander has in the accuracy of the sensor alert. Secondly, knowledge of a massive attack, as opposed to a very small one, will clearly affect the manner in which the commander chooses to respond.

Appendix I: Sensitivity Analysis Details

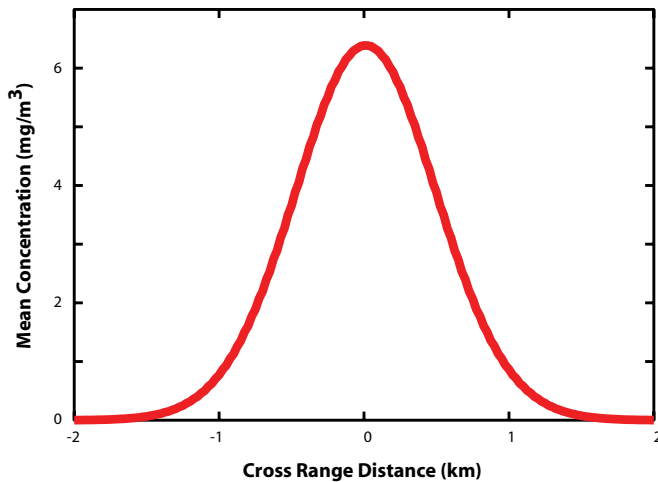


Figure A1.1 Mean agent (*Bacillus anthracis*) concentration (μ_c) along a transverse line 2 km from the agent release point and at a time 1575 s after the agent release when the mean concentration reaches its maximum value. The wind speed is 3.5 m/s.

The Hazard Prediction and Assessment Capability (HPAC) program generates a statistical description of the propagation of biological or chemical agents in the troposphere.¹³ The output from HPAC is defined in terms of the clipped-Gaussian distribution function. It includes the time-dependent values for the mean (μ_c) and the standard deviation (σ_c) of the concentration at any point within the region encompassed by the airborne material.

Figure A1.1 shows a plot of the mean agent (*Bacillus anthracis*) concentration for the deliberate defense scenario (Scenario 3). The concentration is plotted along a transverse line 2 km from the agent release point and 1575 s after the release into a mean wind of 3.5 m/s.

Note that the curve in Figure A1.1 does not represent an actual occurrence. Rather, it is a plot of the average of the concentrations over all possible instances at a given point in time. The values of the mean μ_c (plotted in Figure A1.1) and the standard deviation σ_c (not shown) determine the probability distribution of the random variable for the concentration along the transverse line at each point in time. In general, the probability that a random variable will exceed (or fall short of) a specified threshold can be determined from its distribution function.

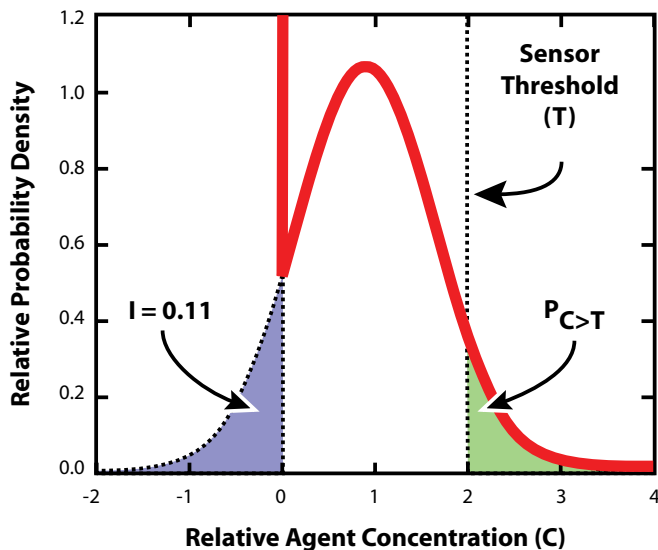


Figure A1.2 The clipped Gaussian relative probability distribution function for the agent concentration, at a particular time and location. The probability that the agent concentration is zero is given by the intermissibility (I). In this case the intermissibility is 11 percent. The probability that the agent concentration exceeds the sensor detection threshold (T) is $P_{C>T}$.

As shown in Figure A1.2, the clipped Gaussian distribution is an ordinary bell curve with the unphysical portion to the left of zero replaced by a delta function at zero. The delta function represents the probability that no agent is present at the corresponding point in time and space. Thus, its amplitude is equal to the integral of the curve over all negative values. The probability that none of the agent is present is called the intermissibility.

The clipped Gaussian distribution function provides the information needed to calculate the probability that the concentration will exceed a specified threshold at the corresponding point in time and space. The area under the curve to the right of the threshold T , as shown Figure A1.2 is

Footnotes

¹³ PC-SCIPUFF Technical Documentation, R.I. Sykes, S.F. Parker, D.S. Henn, C.P. Cerasoli, L.P. Santos, Titan Corporation, Titan Research and Technology Division, P.O. Box 2229, Princeton, New Jersey, September 1998. Support for the implementation of the SCIPUFF algorithms in the HPAC program was provided by the Defense Threat Reduction Agency, Collateral Effects Section.

the probability $P_{C>T}$ that the concentration will exceed the value of T . The integral of the curve to the left of T , which includes the contribution from the delta function, is the probability $1 - P_{C>T}$ that the concentration will not exceed the threshold.

The integral of the bell curve over all real numbers greater than T is given by

$$P_{C>T} = \frac{1}{\sigma} \operatorname{erfc}(T) = \frac{2}{\sigma\sqrt{\pi}} \int_T^{\infty} e^{-\frac{(x-\mu)^2}{\sigma^2}} dx$$

Equation A1.1

where the integrand is the normal distribution function with mean μ and standard deviation σ . (The complementary error function erfc is generally available in any scientific subroutine package.) Note that the variables μ and σ in the above equation are not the same as the mean μ_c and standard deviation σ_c for the clipped Gaussian distribution function. In order to use the erfc function to calculate the probabilities needed for the CBS3 analyses, it is necessary to transform the values of the clipped statistics into the corresponding parameters for the ordinary normal distribution function.

Compute μ and σ

The output from an HPAC simulation consists of statistical information in terms of the clipped Gaussian distribution function at each time and point in a specified spatial grid. Given the values μ_c and σ_c for the mean and standard deviation of the clipped Gaussian, the pair of non-linear equations

$$\begin{aligned} \frac{\sigma}{\sqrt{2\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) + \frac{\mu}{2} \left[1 + \operatorname{erf}\left(\frac{\mu}{\sigma\sqrt{2}}\right)\right] - \mu_c &= 0 \\ \frac{\sigma^2}{2} \left[1 + \operatorname{erf}\left(\frac{\mu}{\sigma\sqrt{2}}\right)\right] + (\mu - \mu_c)\mu_c - \sigma_c^2 &= 0 \end{aligned}$$

Equation A1.2

determine the values of μ and σ for the corresponding normal distribution function.

In extreme cases, the equations for μ and σ are poorly conditioned. Although the calculations can require a significant quantity of computational work, a sufficiently accurate solution can be determined in all useful cases for the CBS3 analyses.

A few of the interesting details regarding the numerical methods are within the scope of this Appendix. Complete algorithms can be found in standard texts on the subject.¹⁴ For the iteration algorithms, the Jacobian matrix for the system of equations is

$$\begin{bmatrix} \frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{\mu}{\sigma\sqrt{2}}\right)\right] & \frac{\sigma}{\sqrt{2\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) \\ \frac{\sigma}{\sqrt{2\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) + \mu_c & \left[1 + \operatorname{erf}\left(\frac{\mu}{\sigma\sqrt{2}}\right)\right] \sigma - \frac{\mu}{\sqrt{2\pi}} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) \end{bmatrix}$$

Equation A1.3

Footnotes

¹⁴ Stoer, J., Bulirsch, R., Introduction to Numerical Analysis, Third Edition, Springer-Verlag (2002).

where it was necessary to use the derivative

$$\frac{d}{dx} \operatorname{erf}(x) = \frac{d}{dx} \left(\frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt \right) = \frac{2}{\sqrt{\pi}} \exp(-x^2)$$

Equation A1.4

of the error function. Alternatively, the equations can be rewritten with the change of variable

$$\xi = \frac{\mu}{\sigma\sqrt{2}}$$

Equation A1.5

to get

$$\begin{aligned} \sigma \exp(-\xi^2) + \xi \sigma \sqrt{\pi} [1 + \operatorname{erf}(\xi)] - \mu_c \sqrt{2\pi} &= 0 \\ \sigma^2 [1 + \operatorname{erf}(\xi)] + 2\mu_c \xi \sigma \sqrt{2} - 2(\mu_c^2 + \sigma_c^2) &= 0 \end{aligned}$$

Equation A1.6

with corresponding Jacobian matrix

$$\begin{bmatrix} \sigma \sqrt{\pi} [1 + \operatorname{erf}(\xi)] & \exp(-\xi^2) + \xi \sqrt{\pi} [1 + \operatorname{erf}(\xi)] \\ \frac{2\sigma^2}{\sqrt{\pi}} \exp(-\xi^2) + 2\mu_c \sigma \sqrt{2} & 2\sigma [1 + \operatorname{erf}(\xi)] + 2\mu_c \xi \sqrt{2} \end{bmatrix}$$

Equation A1.7

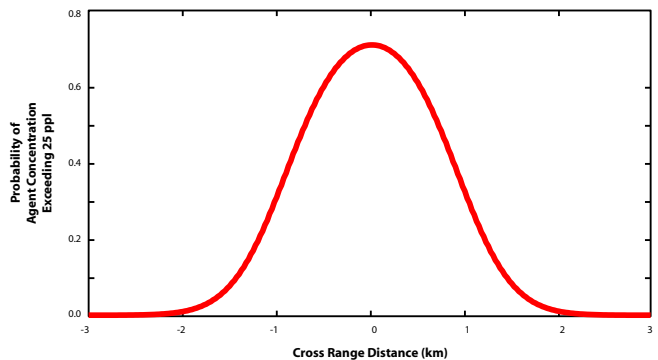
in the variables ξ and σ . The latter expression is better conditioned.

In practice, the values of μ and σ are read from a lookup table in the programs for the CBS3 analyses since the calculations for solving the systems described above are too computationally intensive to be repeated on-the-fly.

Probability of exceeding the threshold

Once the values of the parameters μ and σ for the normal distribution have been calculated, the probability of exceeding the threshold at a point is given by Equation A1.8. Figure A1.3 shows the values corresponding to the plot of the concentrations in Figure A1.1 for a threshold of 25 ppl of the biological agent, *Bacillus anthracis*.

Figure A1.3 Probability of exceeding an instantaneous agent (*Bacillus anthracis*) concentration of 25 ppl along a transverse line 2 km from the agent release point. This probability is shown for a time 1620 seconds after the agent release when the probability of exceeding the 25 ppl concentration is maximum. The wind speed is 3.5 m/s.



The curves displayed in Figure A1.1 and Figure A1.3 vary with time. None of the agent is present until the front edge of the plume reaches the transverse line. The mean concentration and the probability that it will exceed the threshold increase and then subside as the cloud passes. The curves corresponding to the peak value of the mean of the concentration as the agent passes over the transverse line 2 km downwind from the release were chosen for the plots in Figure A1.1 and Figure A1.3. Even so, the likelihood that the concentration will exceed the threshold at any given point is less than 80 percent. Once again, it is important to keep in mind that the data plotted in Figure A1.1 and Figure A1.3 do not correspond to an individual occurrence. Rather, the graphs represent the averages over all possible instances at the point in time given in the figure caption.

The curve in Figure A1.3 shows that the probability that the concentration exceeds the 25 ppl threshold at the 1-km cross-range distance is about 32 percent. Similarly, at -1.5 km the probability is 8 percent. A system containing two sensors, one at each of the two locations, is more likely to detect an attack than a single sensor at either location. If the concentrations at these two points are independent, then the probability of the concentration being greater than the threshold at one or the other of the two locations is given by

$$P_D = 1 - (1 - 0.32)(1 - 0.08) = 0.37$$

Equation A1.8

The independent assumption yields the straightforward formula

$$P_D = 1 - \prod_{j=1}^N (1 - P_j)$$

Equation A1.9

for the probability of crossing the threshold at one or more of a system of N sensors. The value of each P_j in the expression for P_D is given by Equation A1.8. Equation A1.9 says that the probability of exceeding the threshold at one or more locations is one minus the product of the probabilities that it does not reach the threshold at all of the locations. Unfortunately, the assumption of independence upon which Equation A1.9 is based is not always valid.

Detection Probabilities

The direct calculation of the probability of detection by an array of sensors must take the correlation of the concentration into account. The concentration of the contaminant at one location is closely related to the concentration at nearby locations. Thus, the statistical information at points a few meters apart cannot be combined as if they were independent. Rather, the probability for an array of detectors is determined by the multivariate distribution function governed by the covariance matrix for the separate concentrations.

Multivariate Probability Distribution

Let Σ be the positive definite covariance matrix for a random vector $X = (X_1, X_2, \dots, X_n)^T$. Assume X has a multivariate Gaussian distribution defined by the n -tuples of means μ and standard deviations σ . The joint probability that no X_j exceeds its corresponding threshold h_j is given by

$$Q = \frac{1}{\sqrt{|\Sigma|} (2\pi)^n} \int_S \exp\left[-\frac{1}{2} (x-\mu)^T \Sigma^{-1} (x-\mu)\right] dx$$

Equation A1.10

where the integration is over

$$S = \{ x \mid x_j < h_j \text{ for } j=1,2,\dots, n \} \subset R^n$$

Equation A1.11

and $|\Sigma|$ is the determinant of Σ . R^n is the n-dimensional real space.

The joint probability that at least one of the X_j 's will exceed its corresponding threshold h_j is

$$P = 1 - Q$$

Equation A1.12

The multi-dimensional integrals for the probabilities of detection can be calculated for up to about 10 sensor locations. Good results have been obtained for all such cases including high correlation between the components of X .

The probability of detection defined by Equation A1.12 is plotted in Figure A1.4.

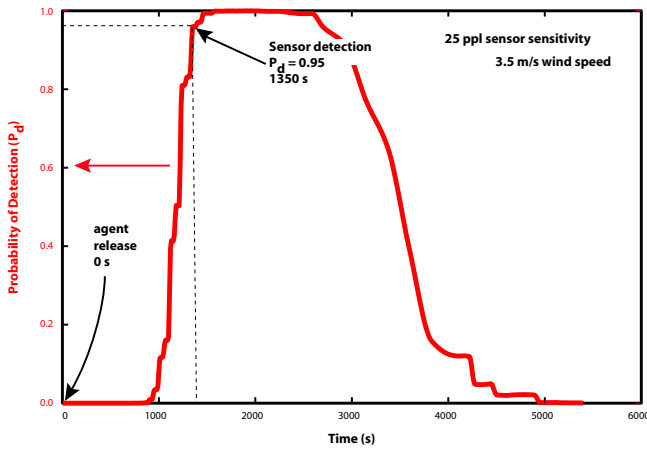


Figure A1.4 Joint probability of the concentration exceeding 25 ppl at one or more sensor locations.

Correlation Scale Length

If L is the spatial correlation scale factor (in units of length) for the concentration at each point within the plume of a contaminant, then the correlation between the concentrations at nearby locations is

$$r = \exp\left(-\frac{|\Delta x|}{L}\right)$$

Equation A1.13

where Δx is the separation between these distances. By definition, the correlation coefficient between the random variables for the concentration at locations i and j is defined to be

$$r_{i,j} = \frac{\sigma_{i,j}}{\sigma_i \sigma_j}$$

Equation A1.14

where σ_{ij} is the covariance of the probability distribution. The values of σ_i and σ_j are the standard deviations of the concentration at locations i and j , respectively.

Assume that the correlation scale factors and the standard deviations of the concentration are known at each point in a straight-line array of N locations. The entries on the diagonal of the corresponding N by N covariance matrix

$$\Sigma = (\sigma_{i,j})$$

Equation A1.15

are the variances of the concentration at the given locations. Using the above expressions for the correlation coefficient, the off-diagonal entries in the symmetric covariance matrix are given by

$$\sigma_{i,j} = \sigma_i \sigma_j \exp\left(-\frac{|\Delta x_{i,j}|}{L}\right)$$

Equation A1.16

where Δx_{ij} is the separation distance between location i and location j and L is the concentration correlation scale length.

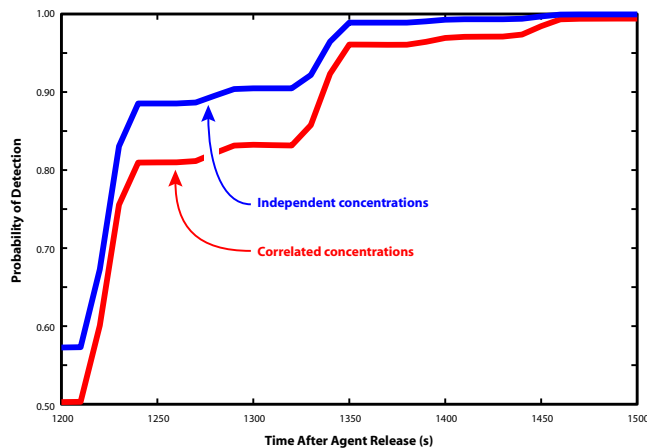


Figure A1.5 The probability of the concentration exceeding a 25 ppl threshold, at one of the sensor locations, for cases in which the agent concentration at these locations are either independent or are correlated over some spatial distance. This plot is an expansion of the plot in Figure A1.4 for independent and correlated concentrations.

The independent assumption yields optimistic values for the probability of detection and for the time at which the 95 percent level of confidence is achieved. The results are shown in Figure A1.5 where the data were calculated using Equations A1.15 and A1.16 for the independent and correlated probabilities of exceeding the concentration threshold.

Summary

Several steps are involved in the probability of detection analyses. The corresponding unclipped parameters are used in the formula for the probability that the concentration will exceed the threshold at any point. The corresponding unclipped statistics define the multivariate distribution function for the probability that the concentration will exceed the threshold at any point. These calculations are repeated for each release distance, sensor spacing, wind speed, and correlation scale length. Finally the results are scaled by the release mass.

Appendix II: False Positive Rate Analysis

While the false positive rate is one of the key metrics of a sensor, it generally receives the least analysis. Generally, the acceptable false positive rate is determined by guessing what the users will tolerate. This appendix describes a process for providing a more analytical estimate of the acceptable false positive rate. The detailed results of this analysis are classified and are not presented here. A separate classified briefing on this analysis and its results has been prepared.¹⁵

For the purpose of this analysis, we define the break-even false positive rate to be that false positive rate for which the cost associated with acquiring and using agent sensors and responding to the false positives is equal to the cost of not having any agent sensors. The break-even false positive rate is dependant on the probability of an agent attack and the details of such an attack (e.g., agent type, amount of agent released, and atmospheric conditions).

The break-even false positive rates for military chemical and biological warning sensors were estimated with two slightly different mathematical relationships that represent two different perspectives: the risk perspective and the cost-benefit perspective. The risk perspective simply balances the benefit of using the agent sensors in the current threat environment against the potential cost of false positives to the current mission. This is appropriate for the commander leading an imminent operation for whom the acquisition, operation, and maintenance cost of the sensors is already realized and the most critical question is whether false positives will harm the mission more than a true positive is likely to help it. In this case, the false positive rate analysis generates the break-even false positive rate vs. the expected probability of an agent attack in the current operation. The cost-benefit perspective balances the benefit of using the agent sensors in their intended operational context against the sum of the annual false positives and the sensor operation and maintenance costs. This perspective is appropriate for those managing the development and acquisition of the sensor system, for whom the longer term point-of-view is most relevant. The result of this analysis is a family of curves showing the tolerable false positive rate per operation vs. the sensor cost per-operation for a set of threat probabilities. Figure A2.1 illustrates the risk perspective analysis and the cost-benefit perspective analysis. The risk perspective results are linear functions of the expected threat probability the slope of which is the ratio of the benefit to the false positive impact. The cost-benefit perspective results are kneed curves that are flat until the sensor operating and maintenance costs rival the false positive costs, at which point tolerable false positives fall off rapidly.

Method	Perspective	Task	Requirements
Risk Analysis	Commander	Weigh sensor alert responses against threat environment	$R_A (I_{udA} - I_{dA}) \geq R_{fp} I_{fp}$
Cost Benefit Analysis	Sensor Development Program Manager	High level comparison of technology performance over time and in a range of conditions	$R_A (I_{udA} - I_{dA}) \geq C_s + R_{fn} I_{fn}$

R_A = rate of agent attacks

R_{fp} = rate of sensor false positives

I_{udA} = impact of undetected attack

I_{dA} = impact of detected attack

I_{fp} = impact of false positive

C_s = cost of sensors (per operation including acquisition, operation and maintenance)

Footnotes

¹⁵ To obtain a copy of the classified briefing, please contact Dr. Mike Shatz at Massachusetts Institute of Technology, Lincoln Laboratory.

The various impacts (l_j) are expressed as monetized costs as given in Equation A2.1.

$$I_j = \sum_i^{N_c} C_i + M_{(D)} \cdot \sum_j^{N_d} d_j + \sum_k^{N_i} M_{l k} \cdot l_k$$

Equation A2.1

The first term in Equation A2.1 is the sum over the various types of hard costs (acquisition, operation, maintenance), the second term is the sum over various delays multiplied by a value function, and the third term is the sum over various types of casualties each multiplied by a value function.

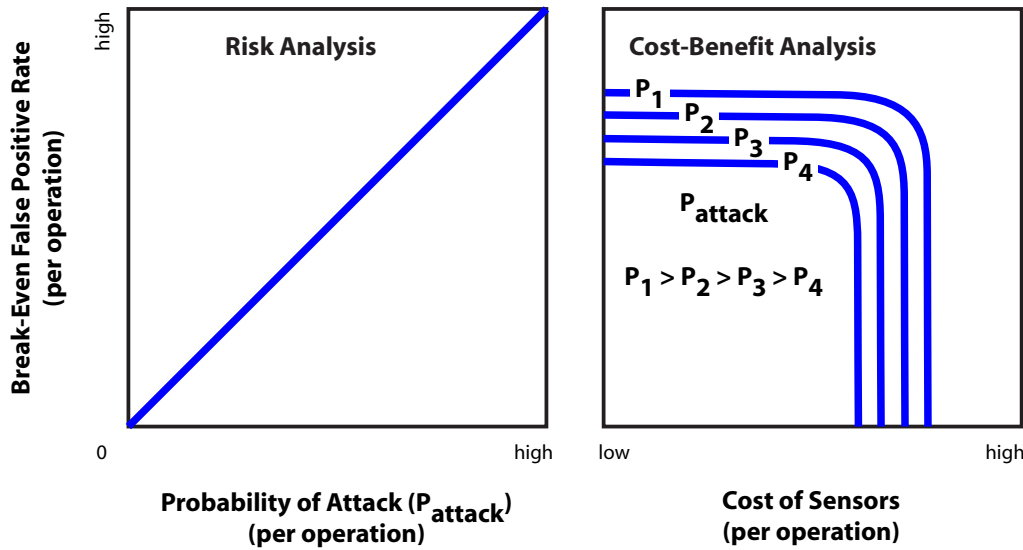


Figure A2.1 Comparison of risk analysis and cost-benefit analysis for evaluating the tolerable false positive rate. P_{attack} is the probability of a biological agent attack.

“Tolerable” false positive rates for military chemical and biological warning sensors are sensitive to the operational context. Two US Army scenarios involving an armored brigade force structure were analyzed for tolerable false positive rates: a movement to contact scenario and a deliberate defense scenario. In the movement to contact scenario, 1 kg of anthrax is released 6-km upwind of the road being traveled by the brigade. This scenario is similar to Scenario 2 (see Section 5.2) except that the attack uses a biological agent. In the deliberate defense scenario, 225 kg of Sarin was released across the front of the actively defended battlefield. This scenario is the same as Scenario #11 (see Section 5.11)

For each scenario, the impacts on military operation of three different events (an undetected attack, a detected attack, and false positives) must be estimated in order to evaluate the risk and cost-benefit relationships. These impacts determine the extent to which a sensor system can succeed or fail and so they define the balance of cost and benefit. The difference between the undetected and detected attack impacts (scaled by the expected threat probability) defined the benefit of employing the system. The false positive impact (scaled by the false positive rate) defined the operational cost, which was then also summed with the operating and maintenance cost for the cost-benefit relationship.

The impact on operations of any of the three events was defined to be the sum of three effects (casualties, delay, and hard costs). Each effect was adjusted to a cost basis for analysis. Casualties were of three types: excess battle casualties due to reduced capabilities while fighting at elevated MOPP, dehydration/exhaustion casualties due to working in MOPP, and casualties due to CB agent exposure. HPAC and Matlab were used to estimate casualties due to CB exposure, and Army force-on-force exercise and field manual data were used to estimate casualties due to reduced effectiveness and due to exhaustion/

dehydration in MOPP4. The cost of casualties included estimates of medical treatment costs, adding death benefits and replacement training for fatalities. The cost of delay was either monetized from estimated excess sustainment costs of the brigade due to having to re-coordinate and re-plan to continue the mission, or allowed to come through in the cost of excess battle casualties due to reduced capabilities in battle rather than as an explicit term. Hard costs incurred in the scenario variants included decontamination (water, decon agent), wear-and-tear on personal protection equipment and collective protection equipment systems, and operation of the M93 Fox CBR reconnaissance system.

In the movement-to-contact scenario, the armored brigade travels along a highway toward the place where they expect to find and engage the enemy. Timeliness is essential in this type of scenario because this mission is to seize momentum from the enemy by finding and surprising them. The threat is an anthrax release several km upwind of the route just in time for the brigade to pass by. No combat is occurring or expected en route, with or without a CB release. If the sensor system alerts, the response plan is to pull over, elevate MOPP, begin confirmatory assays and reconnaissance, and proceed with decontamination of personnel and vehicles until it is clear from assay results that the alert is false, at which time they pick up and continue on. If the alert is a detected attack, they finish decontamination procedures--incurring significant delay--proceed with the mission, and prescribe antibiotics for the brigade as soon as the mission is complete. If there is no sensor alert of the attack, the mission proceeds normally. Those who were exposed to infectious doses would begin falling ill in a few days, relatively few of those would be saved, and the rest would begin antibiotics immediately. The strongest constraint on the false positive rate in this scenario is the highly uncertain but undoubtedly significant and non-linear cost of delay. Threats such as an anthrax release, though, which have the effect of inflicting general force casualties much more than any mission sabotage, but still can be remedied with early detection and lead to higher tolerable false positive rates for moderate threat environments.

In the deliberate defense scenario, the armored brigade is arrayed behind a perimeter that they are actively engaged in battle to defend. Because the brigade as a whole is relatively stationary, delay as its own excess cost has no clear meaning in this scenario; however, combat in MOPP gear does have clear meaning. The threat is a line release of Sarin upwind from the front lines of battle, making contact with the forward units first. If the sensor system alerts, the response plan is to elevate MOPP, begin confirmatory assays and reconnaissance, and begin rotating out units for hasty decontamination procedures. If the assays are negative, then MOPP is decreased, decontamination stops, and the battle continues; though, a large amount of exhaustion, extra battle casualties, and vehicle losses are incurred while fighting in MOPP4. If the assays are positive, fighting and rotating decontamination procedures continue. If the attack is undetected, rear units utilize MOPP when casualties in forward units make it clear that an attack has occurred. Casualties due to chemical attack, exhaustion, and battle as well as vehicle losses are incurred as reconnaissance, rotating decontamination, and casualty treatments begin. Tolerable CB sensor false positive rates for any operational scenario where combat is expected are very low, even for relatively high threat environments because even a few excess battle casualties and vehicle losses due to reduced effectiveness in MOPP gear are very expensive.

In summary, two Army mobile force scenarios were used to estimate tolerable false positive rates for chemical and biological warning sensors. A break-even analysis was done for each scenario, both including and excluding the operation and maintenance costs of the sensors to highlight the difference between an immediate user's perspective and the long-term manager's perspective on the utility of the system. Though potential casualties were the dominant impact, there is a high degree of uncertainty in the cost of delay in the movement-to-contact scenario, which rests on the exact nature of the sensor alert response plan and exactly how a marginal increase in delay would change mission plans. Overall, false positives were found to be significantly less tolerable at all threat conditions in the deliberate defense scenario than in the movement-to-contact scenario because of the high risk associated with having to carry out conventional battle while in MOPP4.

